Fundamental Physics with VERITAS and CTA

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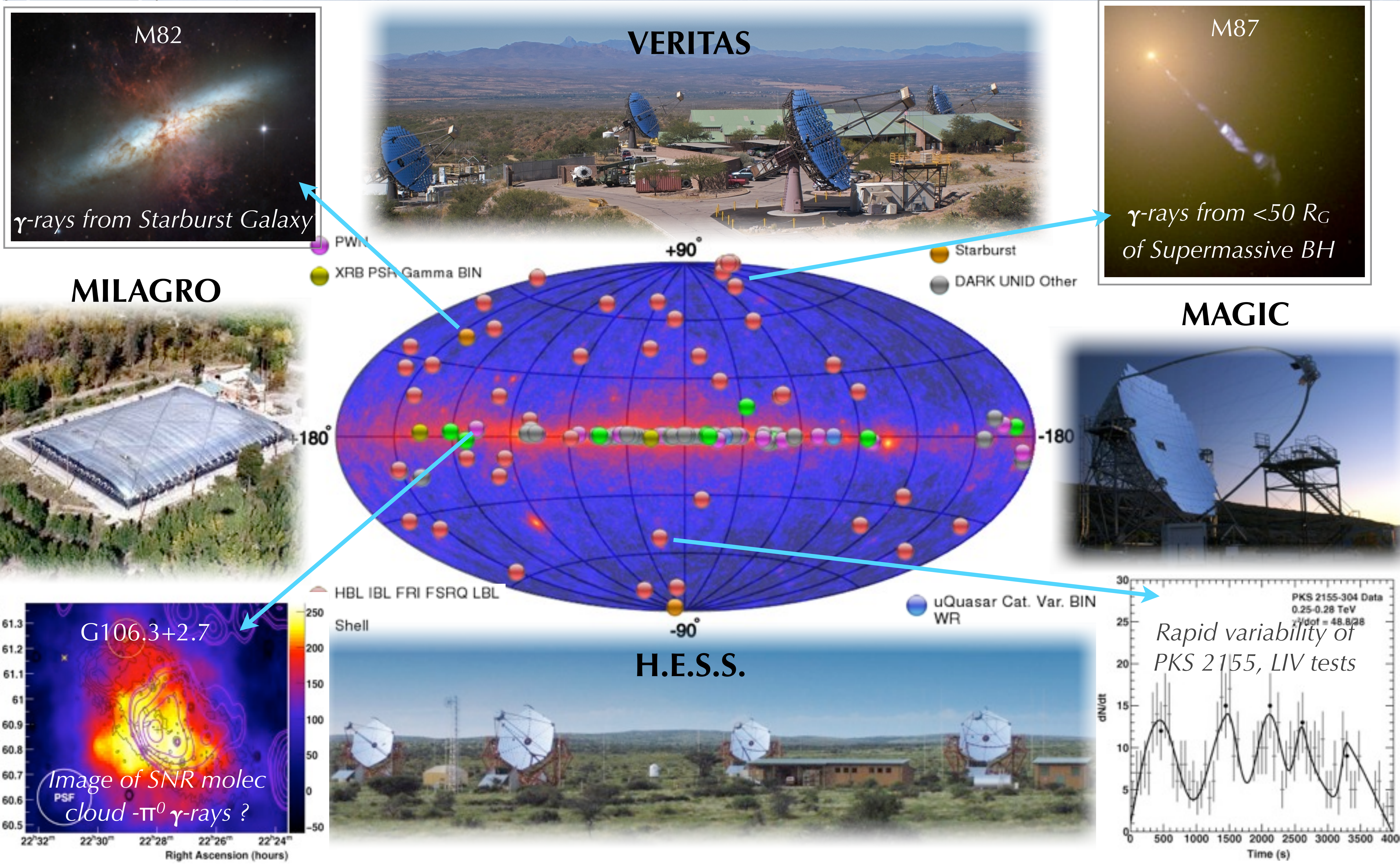
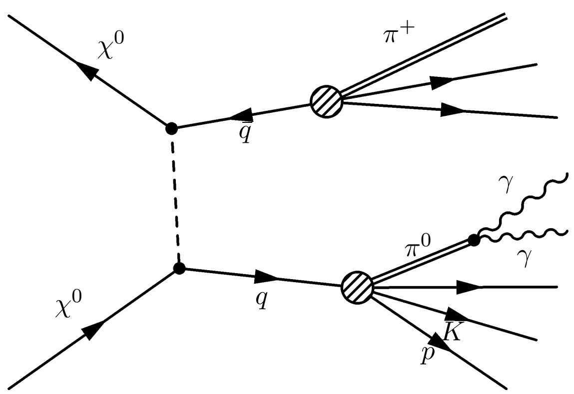
in St. Louis

- **Dark Matter**
- **Lorentz Invariance Violation**
- **Cosmology - Epoch of galaxy formation, primordial magnetic fields**
- **Axion-Like-Particles**
- **VERITAS, CTA and HAWC**

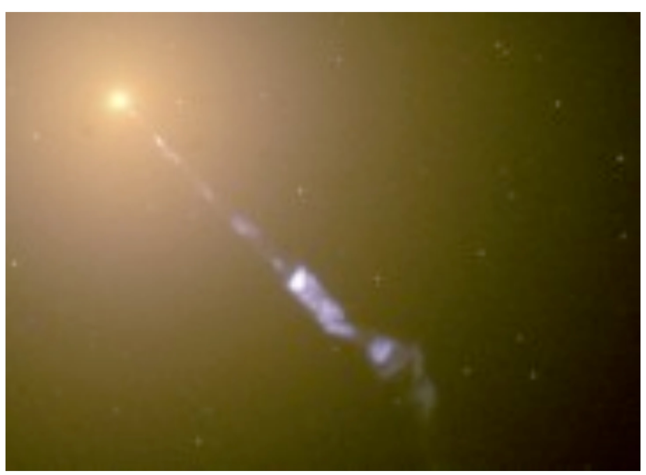
VHE Gamma-Ray Status



Fundamental Physics Probes



Dark matter annihilation

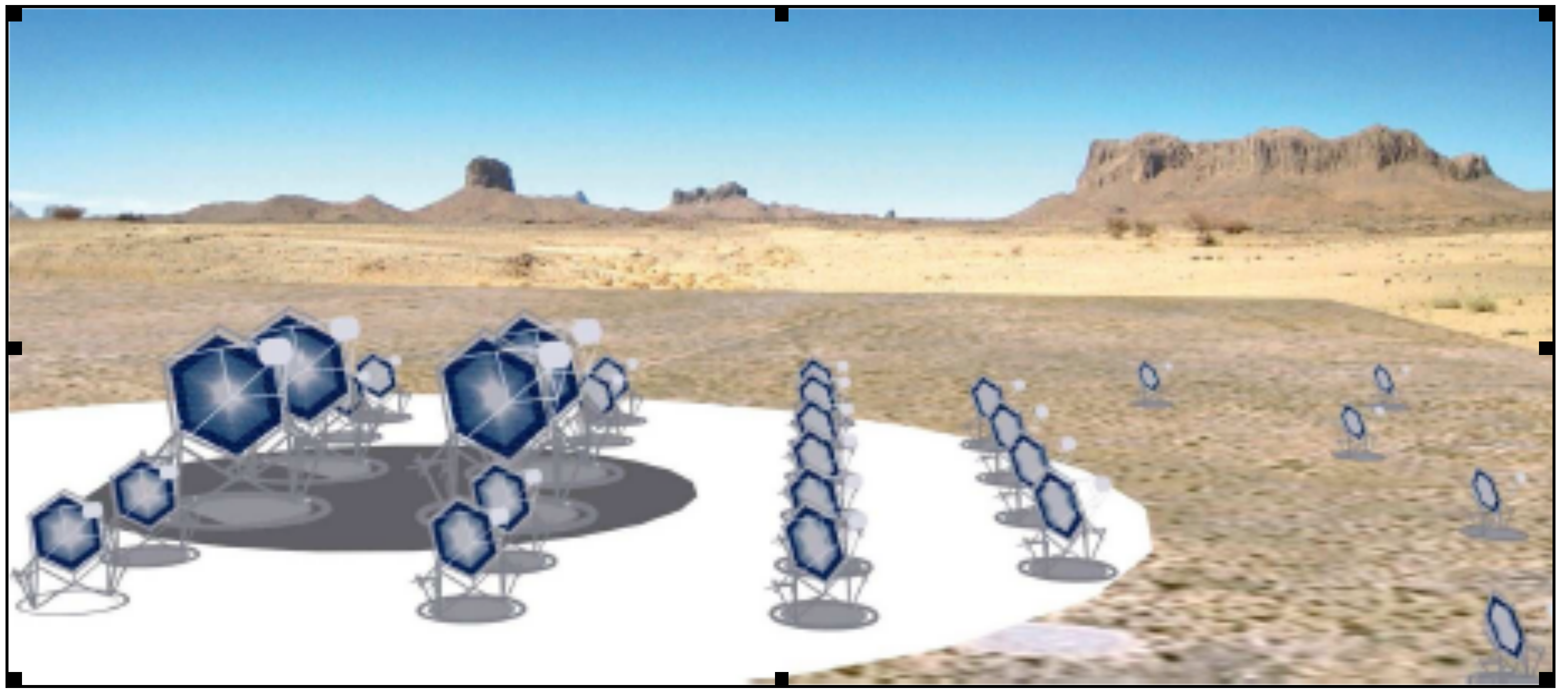


Relativistic jet from AGNs - cosmic accelerators and gamma-ray beams for probing intergalactic space

- **Dark Matter**
  - If LHC detects SUSY, need gamma-rays to connect to DM halos, measure profile.
  - Above LHC reach (~600 GeV) gamma-ray or direct detection needed
  - Gamma-ray cross-section tied directly to decoupling cross-section and relic abundance (unlike nuclear recoil cross section.)
  - Gamma-ray spectrum allows mass measurement and particle ID
- Distant gamma-ray sources (AGNs and GRBs) can be used as beams to probe intergalactic radiation fields (*primordial starlight*), *intergalactic magnetic fields*, TeV-Planck scale physics (*Lorentz invariance violatio*n) and *Axion-like-particles*
  - **Lorentz Invariance Violation** tests - Use fastest transients at highest energy to look for dispersion of light - TeV to Planck scale effects not accessible with accelerators
  - Distortions in gamma-ray spectra from electron-positron pair production provide measurements of **EBL** containing contributions to diffuse background from the time of decoupling, through the star formation history of the universe. Constrain first Population III stars, particle decays
  - Constraints on **Axion-Like-Particles** that would allow VHE photons to escape pair absorption by oscillating to ALPs, to be regenerated in the local galactic field

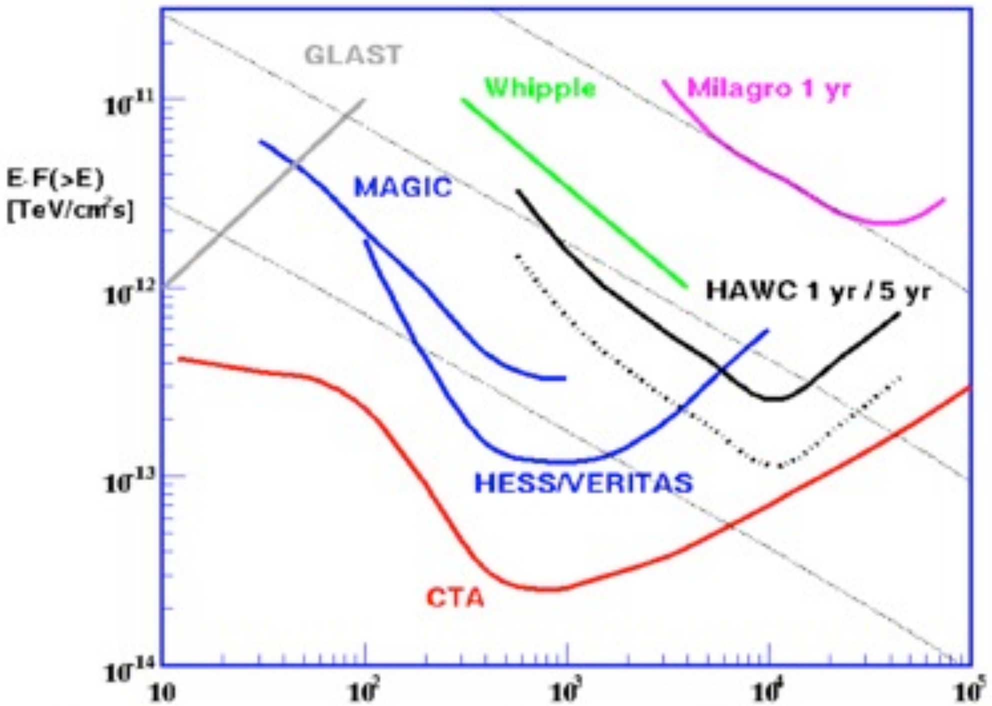
Future Experiments

CTA



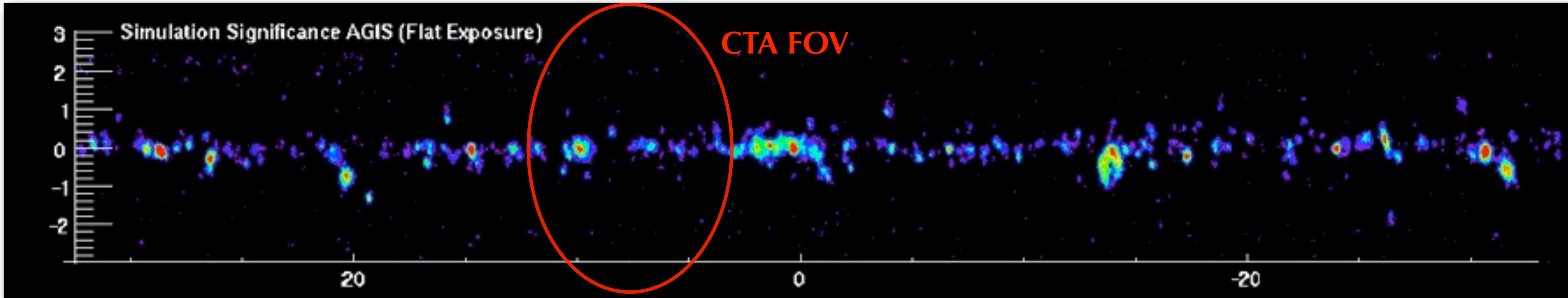
- CTA baseline design consists of
  - 4 x 24m Large Size Telescopes (LSTs) for the lowest energies
  - 23 x 12m Mid-Size Telescopes (MSTs) for medium energies (100 GeV - 10 TeV)
  - 50 x 6m Small-Size Telescopes (SSTs) for high energies (>10 TeV)
- CTA-US will supplement this with 36 more MST telescopes
- HAWC will consist of 300 water tanks at 4100m a.s.l toprovide all-sky survey observations above TeV energies
- As MILAGRO guided HESS, MAGIC and VERITAS HAWC will guide CTA

HAWC



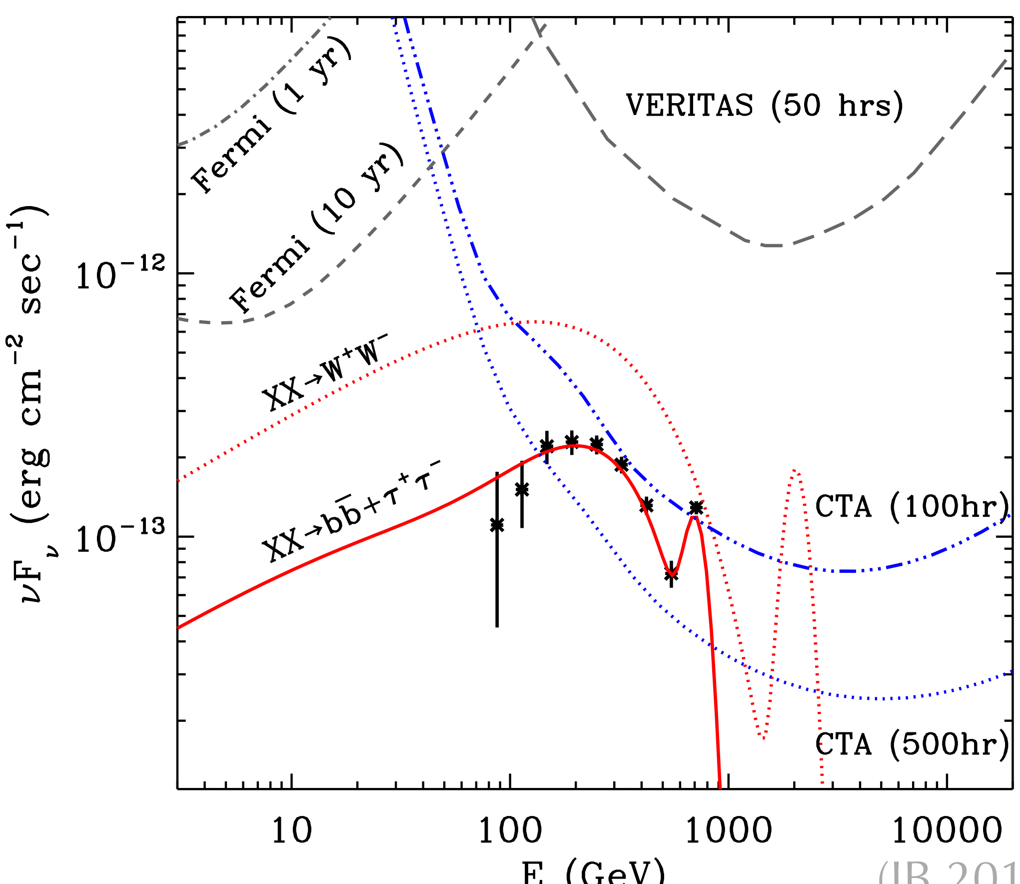
CTA-US Science Drivers

Survey for galaxy - astrophysical sources, unidentified dark accelerators, halo substructure



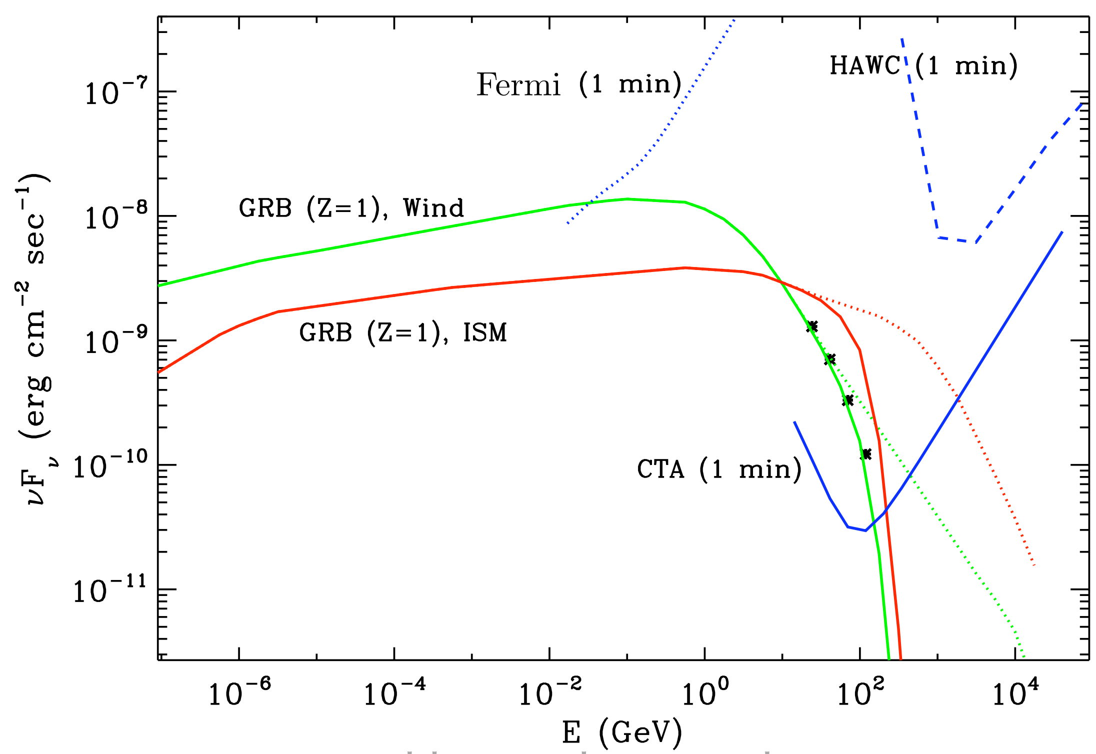
Simulated Sky Map with Improved Angular Resolution, FoV, Sensitivity   Digel, Funk and Hinton

Dark Matter



(JB 2011)

GRBs and Rapid Transients

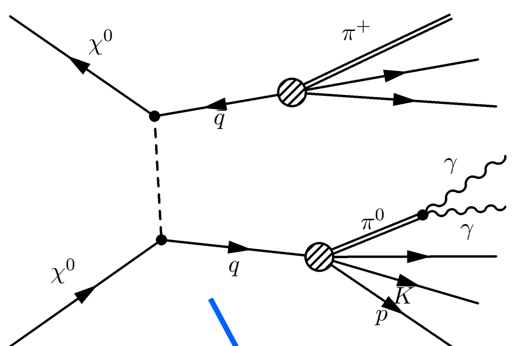


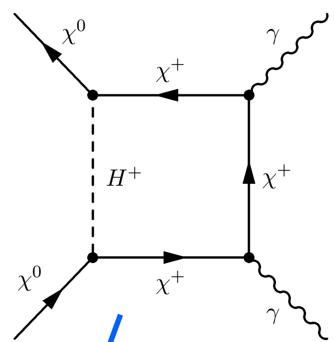
(Buckley et al., APS whitepaper, 2008)

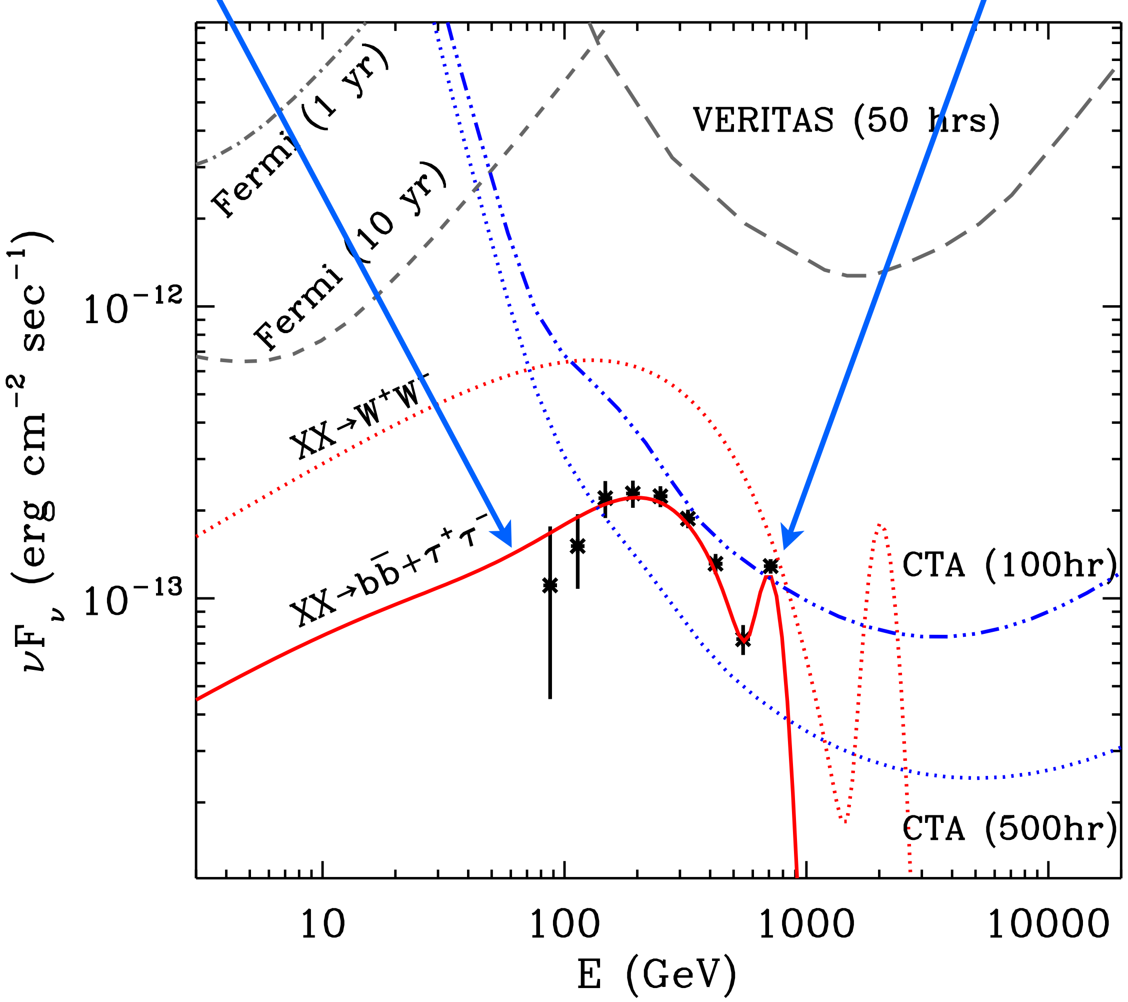
Gamma-rays from DM

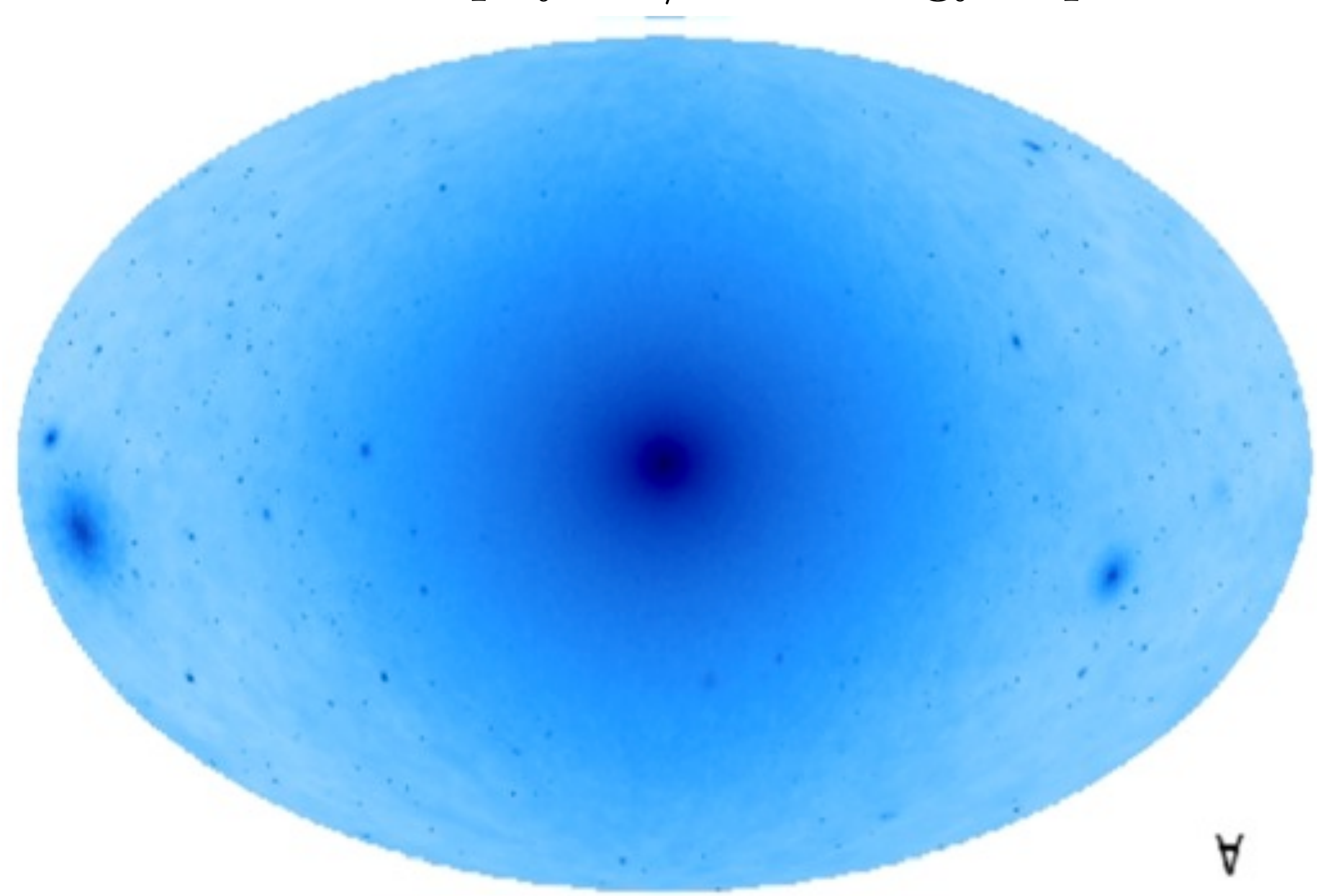
$$E_\gamma \Phi_\gamma(\theta) \approx 10^{-10} \underbrace{\left(E_{\gamma,\mathrm{TeV}} \frac{dN}{dE_{\gamma,\mathrm{TeV}}}\right) \left(\frac{\langle \sigma v \rangle}{10^{-26}\mathrm{cm}^{-3}\mathrm{s}^{-1}}\right) \left(\frac{100\,\mathrm{GeV}}{M_\chi}\right)^2}_{\text{Particle Physics Input}} \underbrace{J(\theta)} \ \mathrm{erg\,cm^{-2}s^{-1}sr^{-1}}$$

$$J(\theta) = \underbrace{\frac{1}{8.5\,\mathrm{kpc}} \left(\frac{1}{0.3\,\mathrm{GeV/cm^3}}\right)^2 \int_{\text{line of sight}} \rho^2(l)dl(\theta)}_{\text{Astrophysics/Cosmology Input}}$$



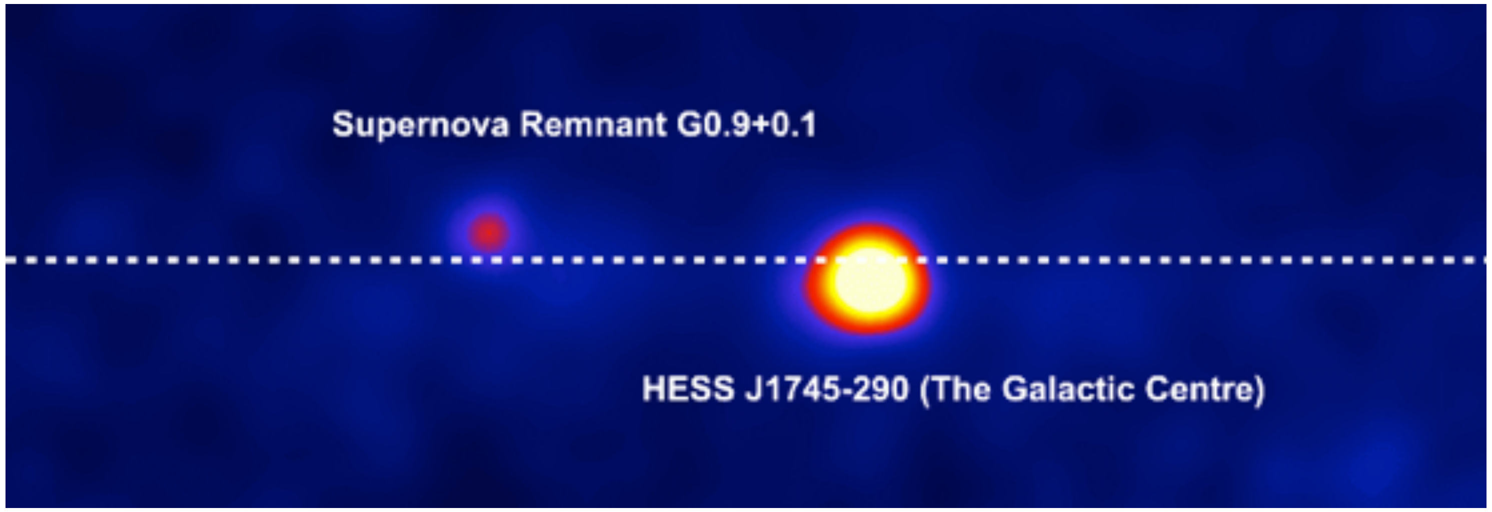




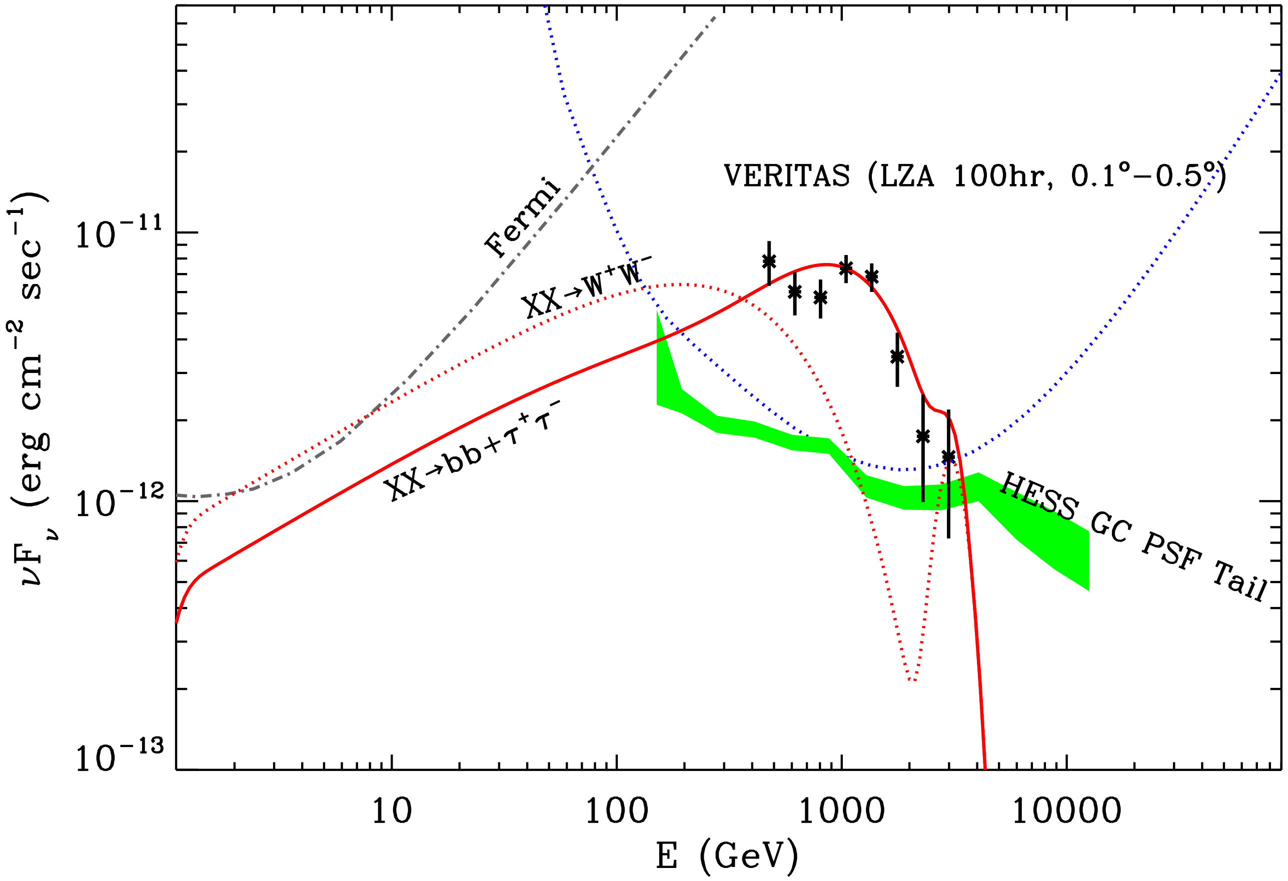


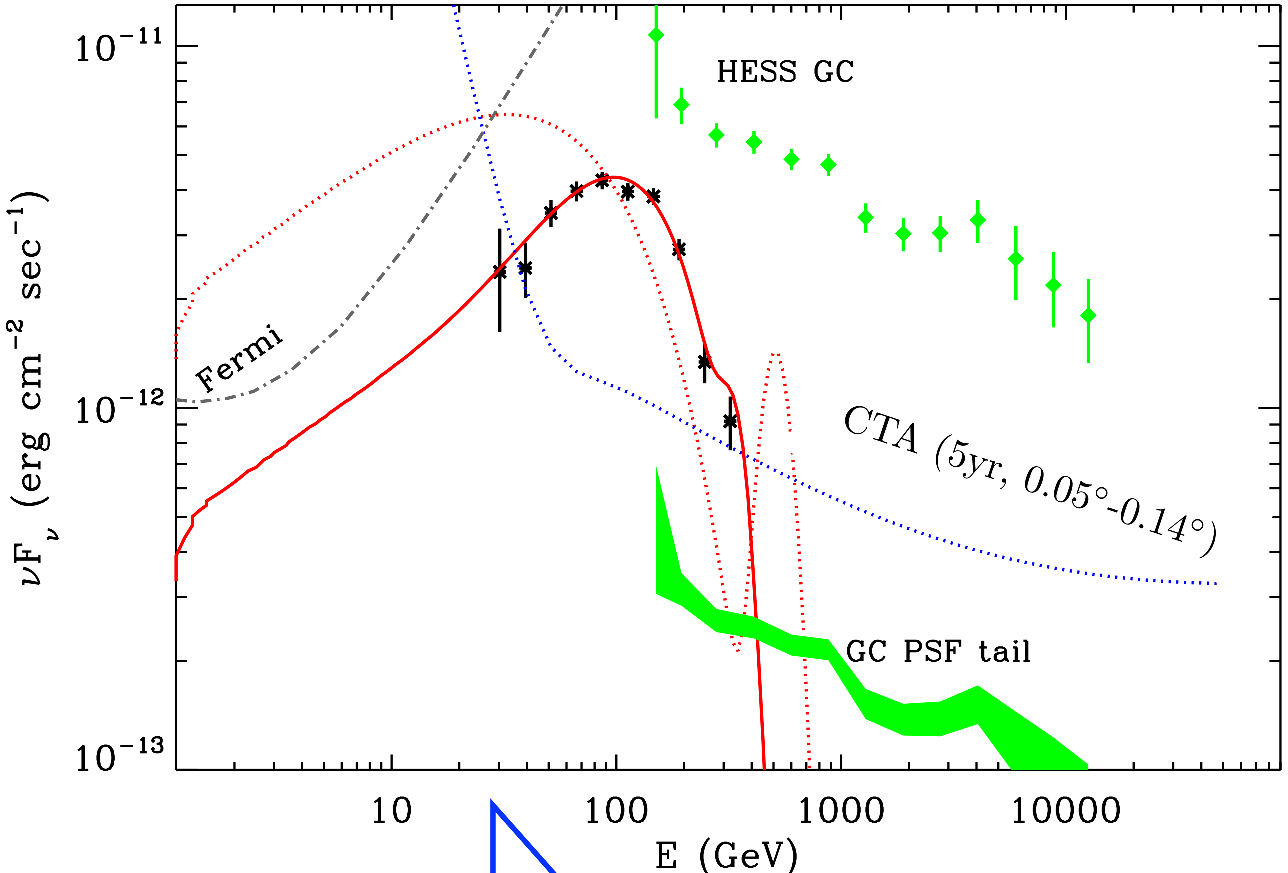
Line-of-sight integral of ρ^2 for a Milky-Way-like halo in the VL Lactea II ΛCDM N-body simulations (Kuhlen et al.)

GC DM Prospects



Bright source at galactic center with spectrum extending up to 20 GeV - not well fit by DM, but DM may still provide a good target





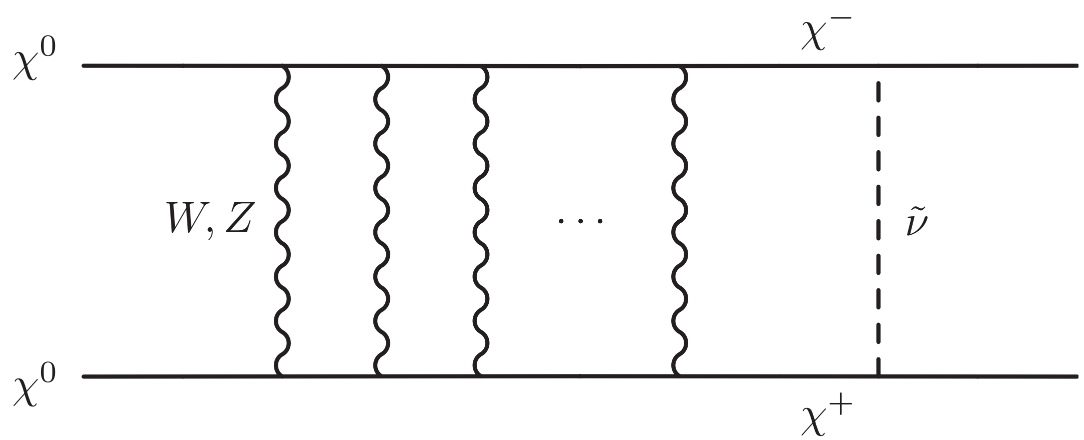
Angular resolution + sensitivity + southern hemisphere

VERITAS sensitivity to GC region excluding point source for 3 TeV neutralinos with ~x10 boost (Sommerfeld or Astrophysical boost)

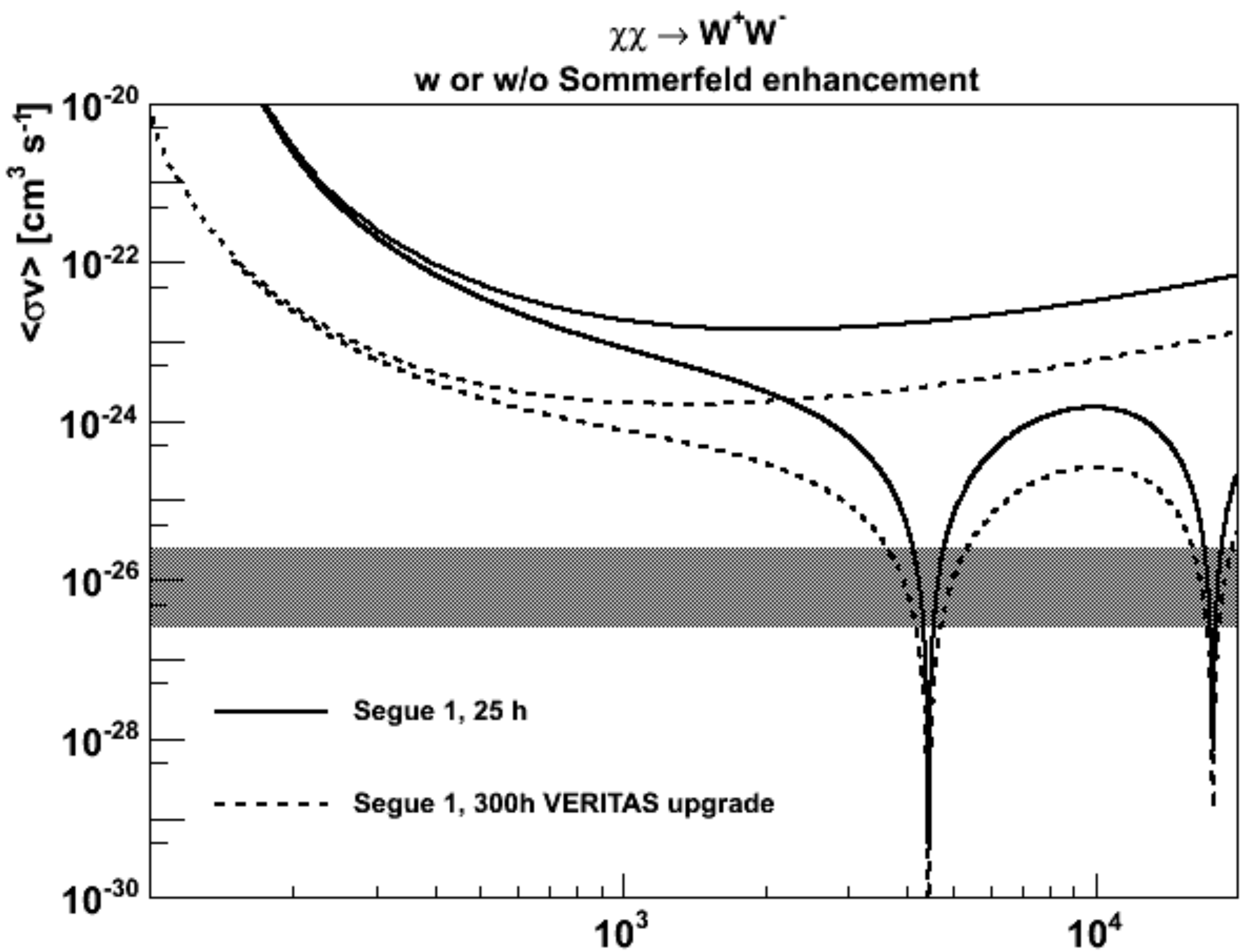
CTA can detect ~>100-200 GeV neutralinos with no boost

Sommerfeld Enhancement

At sufficiently high neutralino masses, the W and Z can act as carriers of a long-range (Yukawa-like) for resulting in a velocity dependent enhancement in cross section (1/v or even $1/v^2$ enhancement near resonance)



Lattanzi and Silk, PRD 79, 083523 (2009), Profumo (2005)

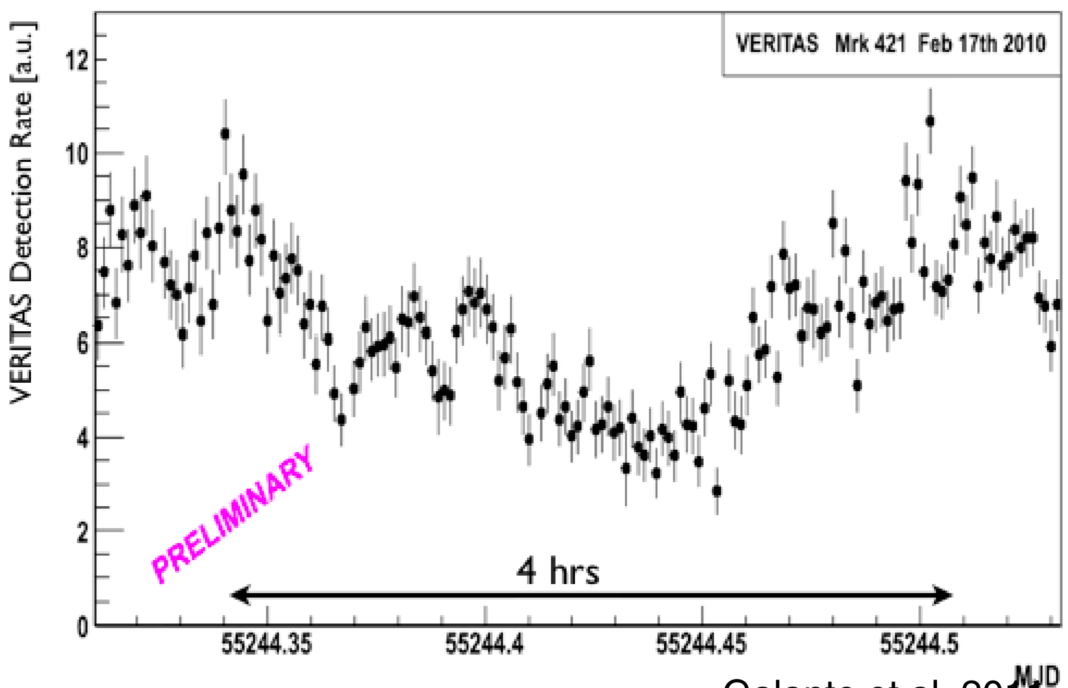


(Courtesy Matthieu Vivier)

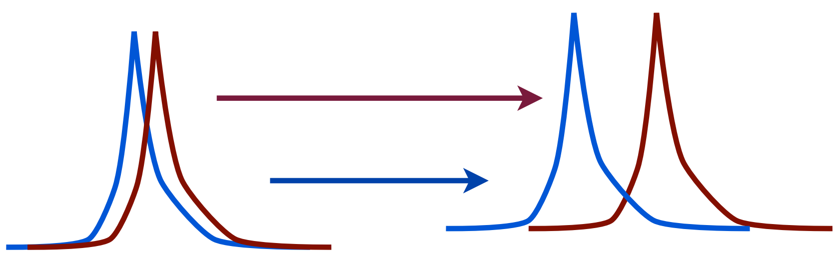
- At high mass, expect Sommerfeld enhancement from W, Z exchange for standard neutralinos can give large enhancement in cross section, larger at small velocities in smaller halo substructure (e.g., Dwarfs)
- While HAWC will have a relatively high threshold, would be sensitive to some models at > several TeV where Sommerfeld enhancement is possibly quite large

Lorentz Invariance Violation

February 2010 Observations of Mrk 421



Galante et al. 2011



- GUTs produce effects that are often only observable at the Planck scale, well beyond the reach of terrestrial accelerators.
- In the electromagnetic sector, these effects can show up as a vacuum dispersion relation for the propagation of light - e.g., a speed of light that depends on photon energy and polarization.

$$E^2 = c^2 p^2 \ \ or \ \ H = cp$$

$$\text{From hamiltonian mechanics}: \dot{x} = \frac{\partial H}{\partial p} = c$$

$$\text{LIV} \Rightarrow \qquad \dot{x} = \frac{\partial H}{\partial p} \sim c\left(1 \pm \xi \frac{E}{M_{\rm pl}} + \mathcal{O}\left(\frac{E}{M_{\rm pl}}\right)^2\right)$$

$$\Delta t = \frac{\xi \Delta E}{2 M_{\rm pl}^2 H_0} \int_0^z \frac{(1+z')dz'}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}} + \frac{3\zeta \Delta E^2}{2 M_{\rm pl}^2 H_0} \int_0^z \frac{(1+z')^2 dz'}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}}$$

- To best constrain these effects, one should look for the *shortest transients at the highest energies from the most distant sources.*

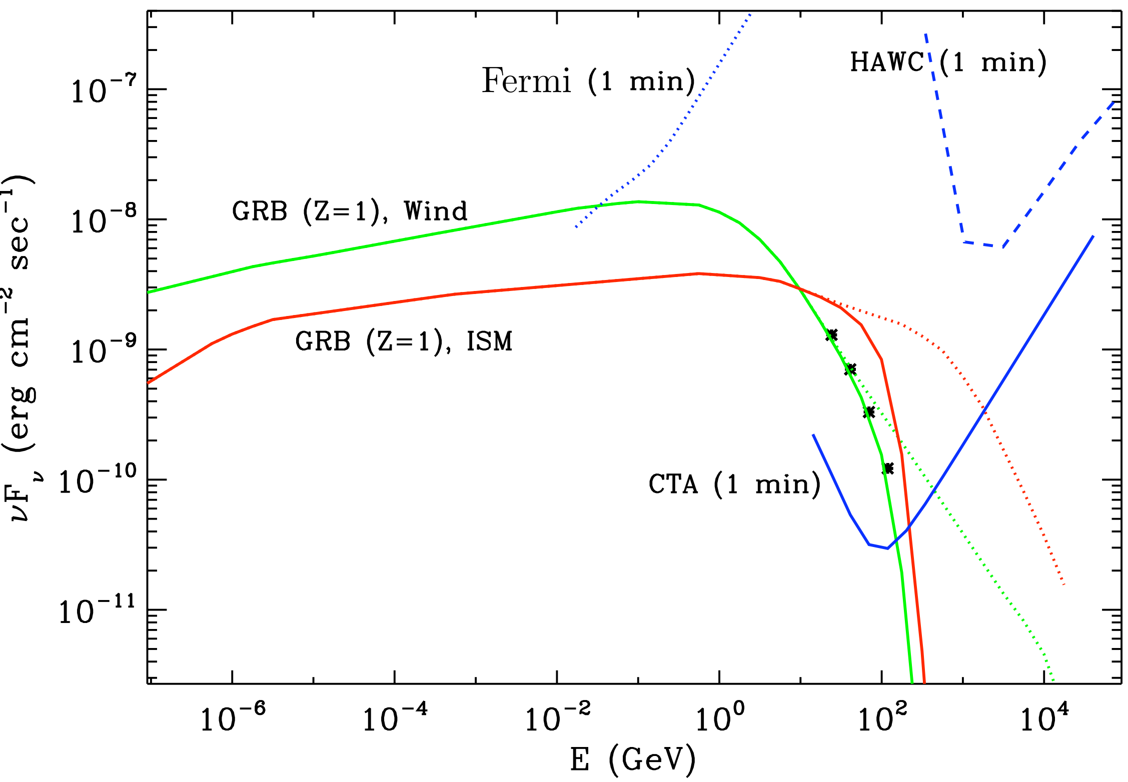
Table 1: Estimated sensitivity to the energy scale of LIV from observations of GRBs, blazars flares and pulsars with *Fermi* and VERITAS.

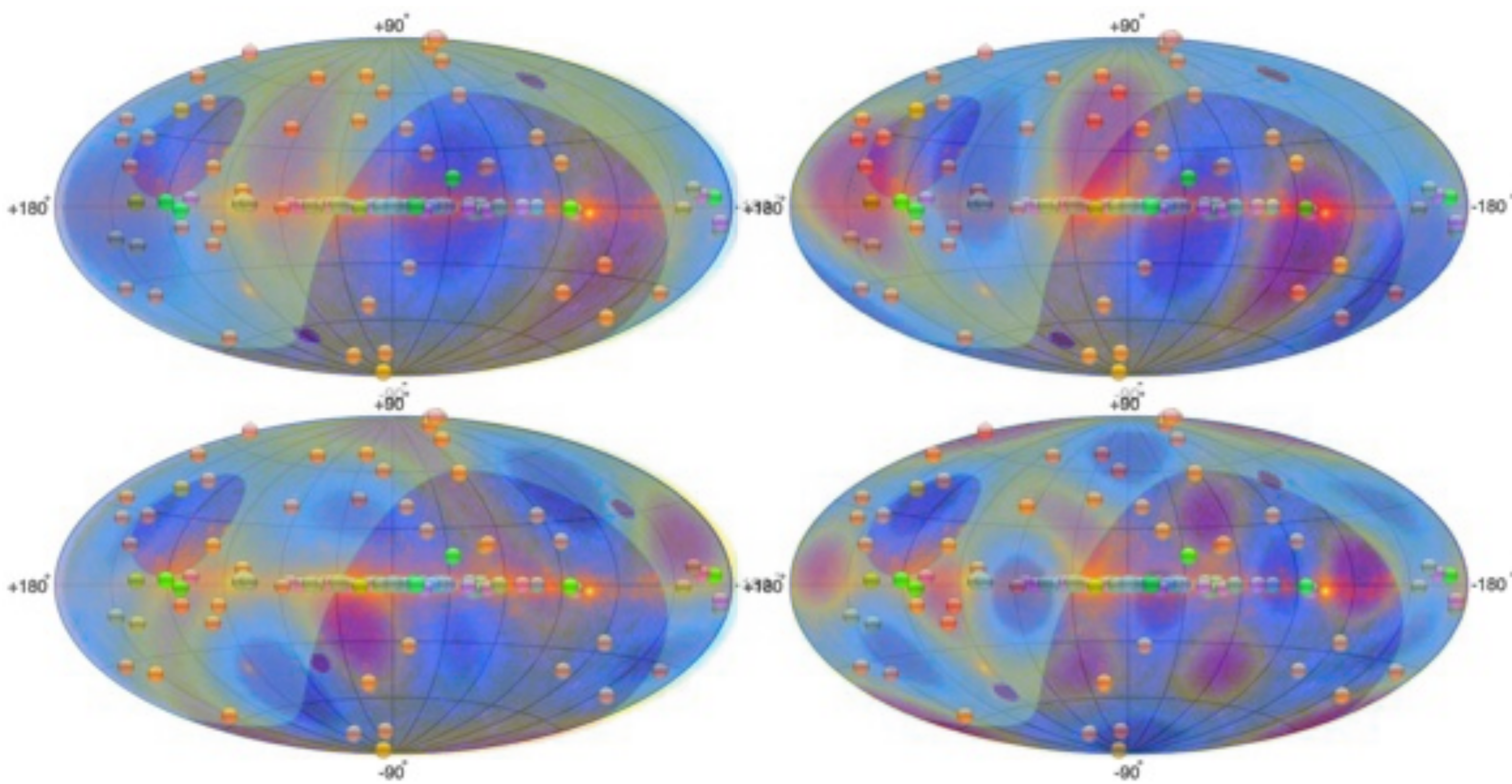
	Observatory	z (d_L)	Δt	ΔE	E_l	E_q
GRB	*Fermi*	0.900 (1.8×10^{26} m)	1 s	30 GeV	1.8×10^{19} GeV	2.3×10^{10} GeV
GRB	VERITAS	0.500 (8.7×10^{25} m)	10 s	200 GeV	0.6×10^{19} GeV	3.4×10^{10} GeV
Mrk 421	VERITAS	0.030 (4.0×10^{24} m)	60 s	1 TeV	2.0×10^{17} GeV	2.0×10^{10} GeV
Crab Pulsar	VERITAS	2.0 kpc (6.2×10^{19} m)	10^{-3} s	100 GeV	2.1×10^{17} GeV	1.4×10^{9} GeV

Key Measurements

- GRBs and AGNs will provide the best probes.

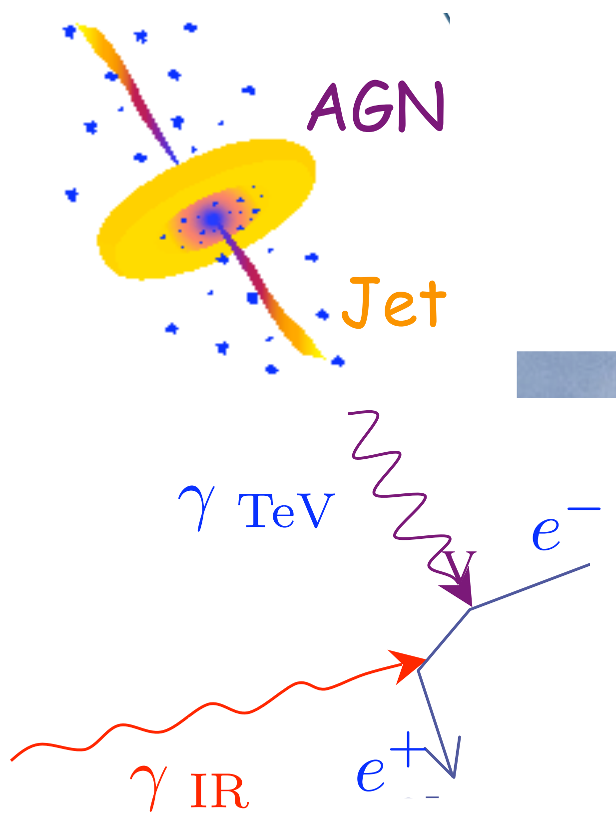
- In general one must allow scalar terms, subluminal and superluminal terms in the dispersion, *polarization* dependent terms, and *anisotropic terms* (coefficients in a spherical harmonic expansion indicating, e.g., a preferred direction in space)



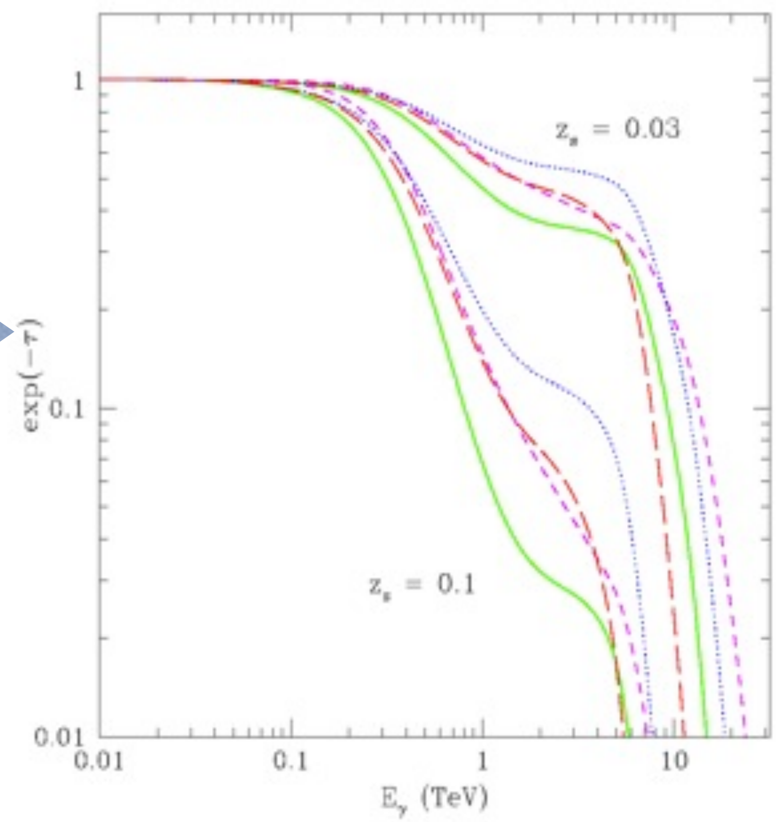


- Combine many measurements of the shortest variability timescales of AGN at different points in the sky to obtain limits on the coefficients of the Y_{lm}

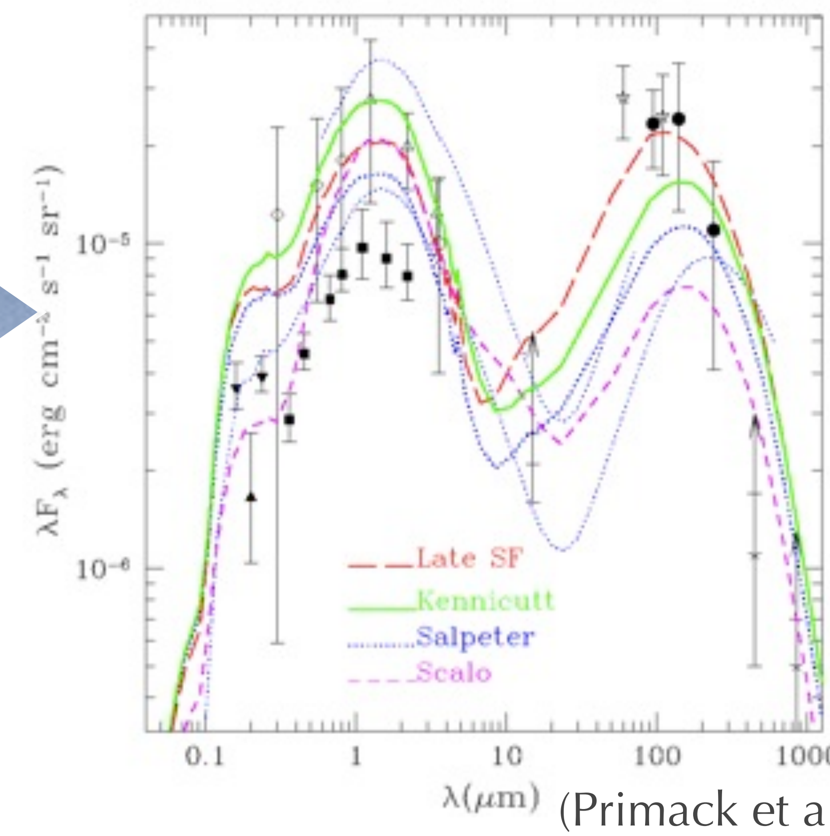
Extragalactic Background Light



Survival probability for gamma-rays



Corresponding EBL spectrum



(Primack et al.)

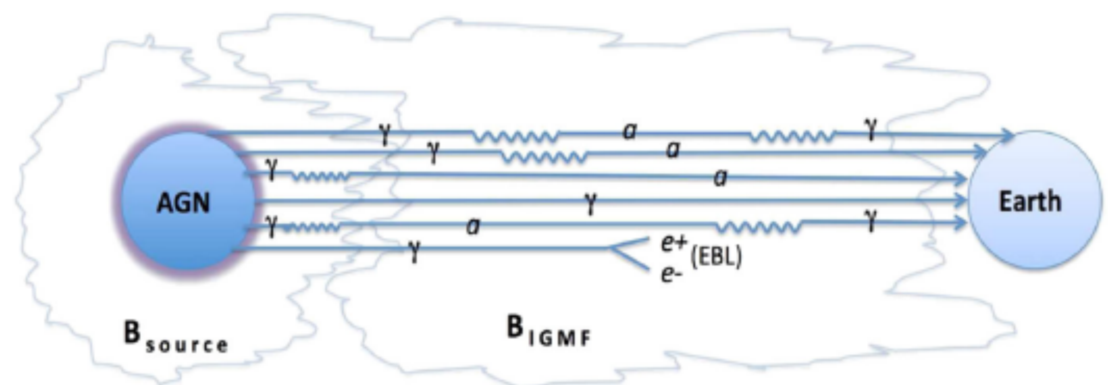
- Integalactic space is filled with redshifted primordial starlight (UV to IR) imprinted with the integral with all radiative processes that occurred after decoupling - *a cousin of the CMB.*
- Pair-production in intergalactic space causes absorption and spectral cutoffs that move to lower energy as the redshift increases.
- If one knows something about the source spectrum, can constrain, even measure, the spectrum of the EBL.
- Can do cosmology by constraining star formation history and any new particle physics scenarios that yield a contribution to the EBL - *the ultimate calorimeter of all eV-scale physics!*

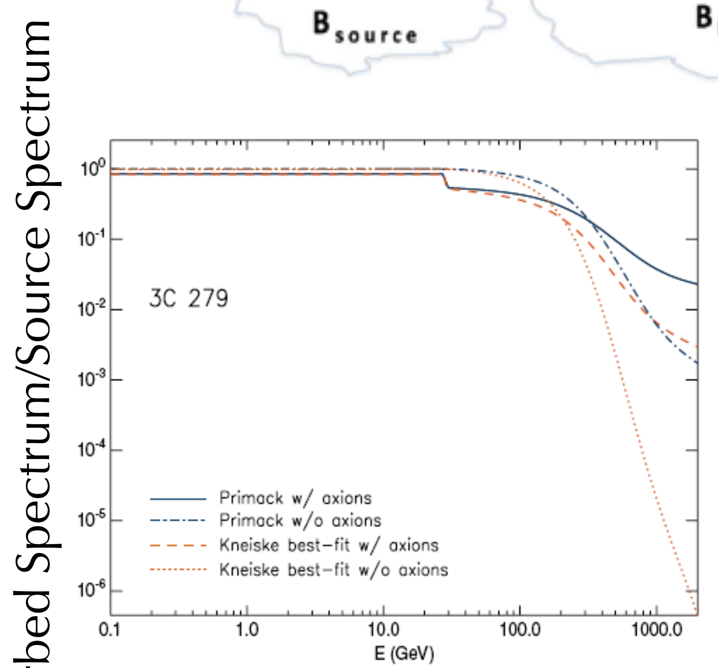
Photon-Axion Mixing

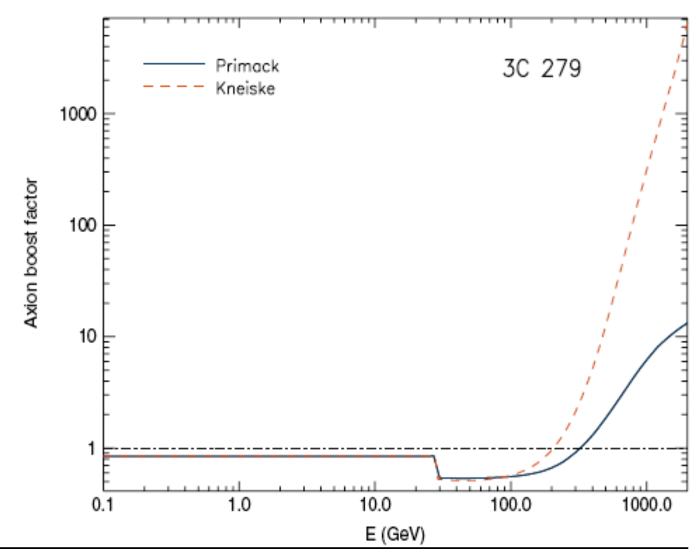
Hooper and Serpico, PRL 99, 231102 (2007)

Sanchez-Conde, Paneque, Bloom, Prada & Dominguez, Phys. Rev. D 79 (2009) 123511

- Photon-ALP mixing can happen at the source, or during photon propagation in the presence of intergalactic magnetic field.
- One signature of this effect will be a relatively sharp drop of ~30% in the spectrum between 1 and 100 GeV.
- Another effect is that mixing could make some photons travel to Earth as axions and then convert back to photons. Axions would not be attenuated by EBL. Therefore, one could expect to see less EBL absorption than expected at E~1TeV for distant sources. The boost effect could be of factor ~100 in the most optimistic scenarios.

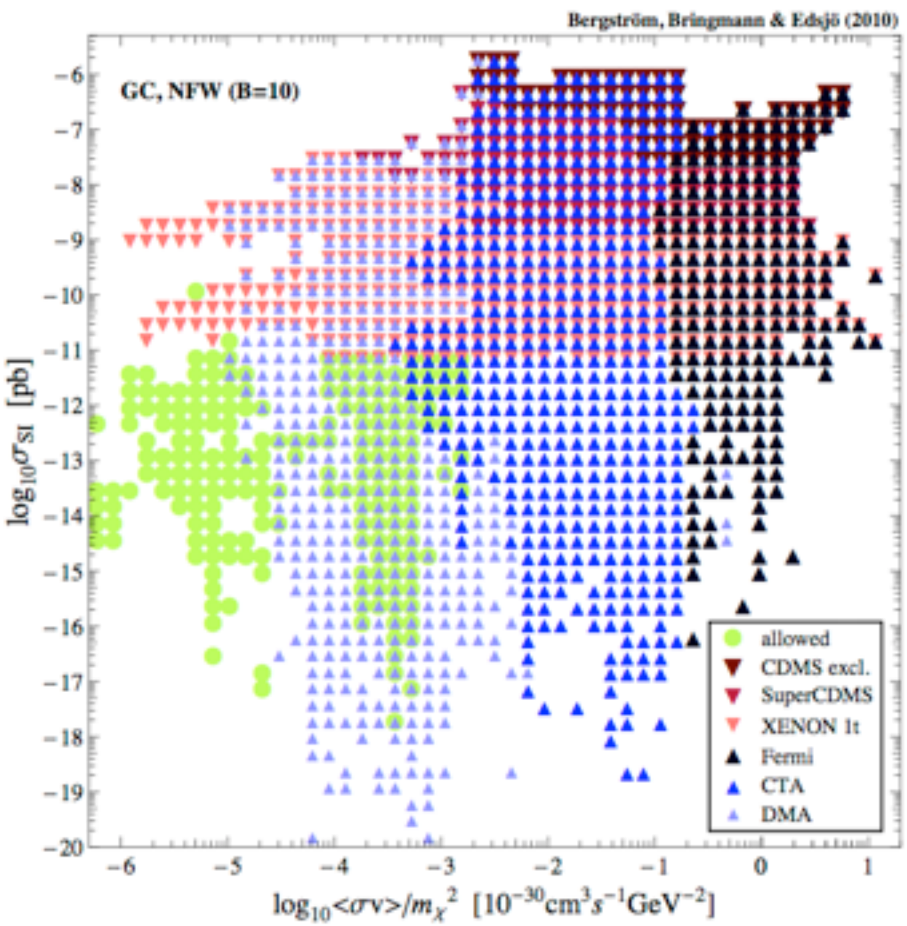






The flux increase due to axions propagating through EBL could be tested with VERITAS by observing distant sources. The effect could be disentangled from our ignorance of EBL density by seeing the effect in multiple sources at different z.

Conclusions



"...We also show the remarkable, and somewhat surprising, fact that indirect detection rates for gamma-ray detection of dark matter annihilation in the galactic halo (or sub-halos) are very weakly correlated with direct detection rates. *This means that a dedicated gamma-ray detector for dark matter detection may probe from an orthogonal direction the parameter space of viable dark matter models, down to direct detection levels that would never be realistically achievable otherwise.*"

[hep-ph] arXiv:1011.4514 L. Bergstrom et al.

- TeV gamma-ray measurements are sensitive to fundamental TeV-scale physics beyond the reach of terrestrial accelerators.
- Disclaimer: *We also do astrophysics* of the most exotic phenomena in the universe ranging including supermassive black holes, compact objects, exploding stars, and GRBs.
- Significant technical overlap with HEP (e.g., LAPPD project, cryogenic DM detectors)
- Gamma-ray measurements address numerous topics in fundamental physics: Dark Matter, Lorentz-invariance violation, ALPs and Cosmology - history of star formation, primordial magnetic fields.
- Any comprehensive program for DM must include gamma-ray measurements!

Backup Slides

Lorentz Invariance Violation

- Since there is no complete theory, it is useful to follow the framework of Kostelecky and collaborators, where one considers generic terms in the Electromagnetic sector of the Lagrangian:

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\epsilon^{\kappa\lambda\mu\nu}A_{\lambda}\left(\hat{\boldsymbol{k}}_{AF}\right)_{\kappa}F_{\mu\nu} - \frac{1}{4}F_{\kappa\lambda}\left(\hat{\boldsymbol{k}}_{F}\right)^{\kappa\lambda\mu\nu}F_{\mu\nu},$$

Dispersion relation (momentum versus frequency)

$$p(\omega) \approx \left[1 + \varsigma^0 \mp \sqrt{\left(\varsigma^1\right)^2 + \left(\varsigma^2\right)^2 + \left(\varsigma^3\right)^2}\,\right]\omega,$$

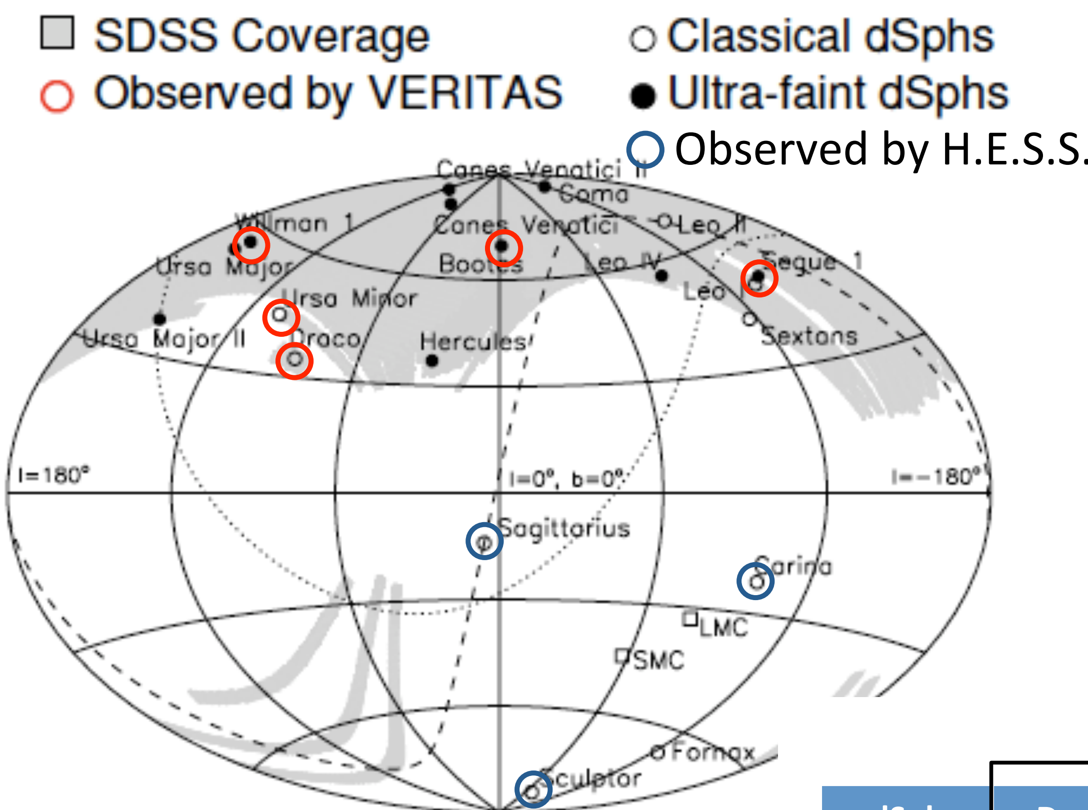
CPT even
$$\varsigma^0 = \sum_{djm} \omega^{d-4}\,{}_0Y_{jm}(\hat{\boldsymbol{n}})k^{(d)}_{(I)jm},$$
Non-birefringent components

$$\varsigma^1 \pm i\varsigma^2 = \sum_{djm} \omega^{d-4}\,{}_{\pm 2}Y_{jm}(\hat{\boldsymbol{n}})\left(k^{(d)}_{(E)jm} \mp ik^{(d)}_{(B)jm}\right),$$

CPT odd
$$\varsigma^3 = \sum_{djm} \omega^{d-4}\,{}_0Y_{jm}(\hat{\boldsymbol{n}})k^{(d)}_{(V)jm},$$

Related to Stokes Parameters
$\zeta^1 = Q,\ \zeta^2 = U,\ \zeta^3 = V$

Dwarf Upper Limits



Belokurov et al. (2007)

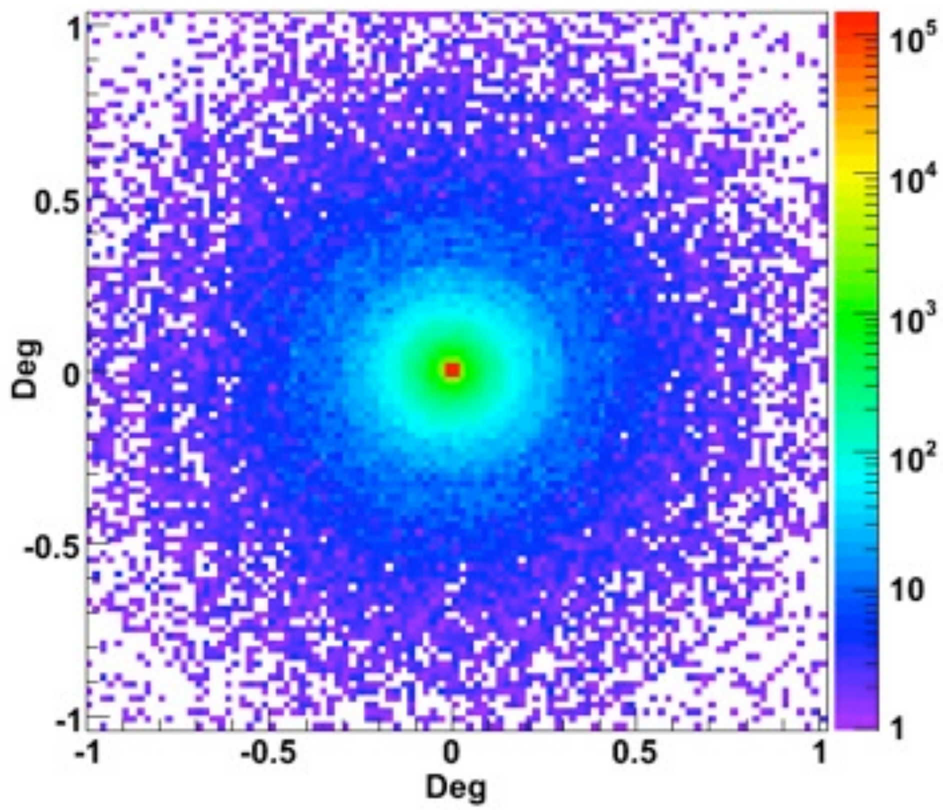
- Dwarf satellites of the Milky Way are the most promising DM targets outside of the Galactic Center
- Dark-Matter dominated objects with mass to light ratios of more than 100
- DM Distribution is tightly constrained by stellar velocity dispersion measurements the map out the DM gravitational potential
- Clean sources with limited uncertainties, but currently one to two orders of magnitude beyond the reach of Fermi, VERITAS or HESS

	VERITAS					HESS			
dSph	Draco	Ursa Minor	Bootes I	Willman	Segue I	Sgr	Carina	Sculptor	Canis Major
Distance (kpc)	82	66	62	38	23	24	101	79	8
DM profile	NFW	NFW	NFW	NFW	Einasto	NFW/ Core	NFW	NFW	NFW
$\log_{10}\langle J\rangle$ (GeV^2 cm^{-5})	18.2	18.4	18.1	18.9	19	19.3/ 20.8	17.6	18.5	18.0
T_{obs} (h)	18.4	18.9	14.3	13.7	25.0	11.0	14.8	11.8	9.6
Ann. channel	$\tau^+\tau^-$, bbar	$\tau^+\tau^-$, bbar	$\tau^+\tau^-$, bbar	$\tau^+\tau^-$, bbar	$\tau^+\tau^-$, bbar	W^+W^-	W^+W^-	W^+W^-	W^+W^-
$\langle\sigma v\rangle^{95\%}$ (cm^3 s^{-1})	5×10^{-23}	2×10^{-23}	5×10^{-22}	10^{-23}	8×10^{-24}	10^{-23}/ 2×10^{-24}	2×10^{-22}	6×10^{-23}	10^{-23}

Pair Halos

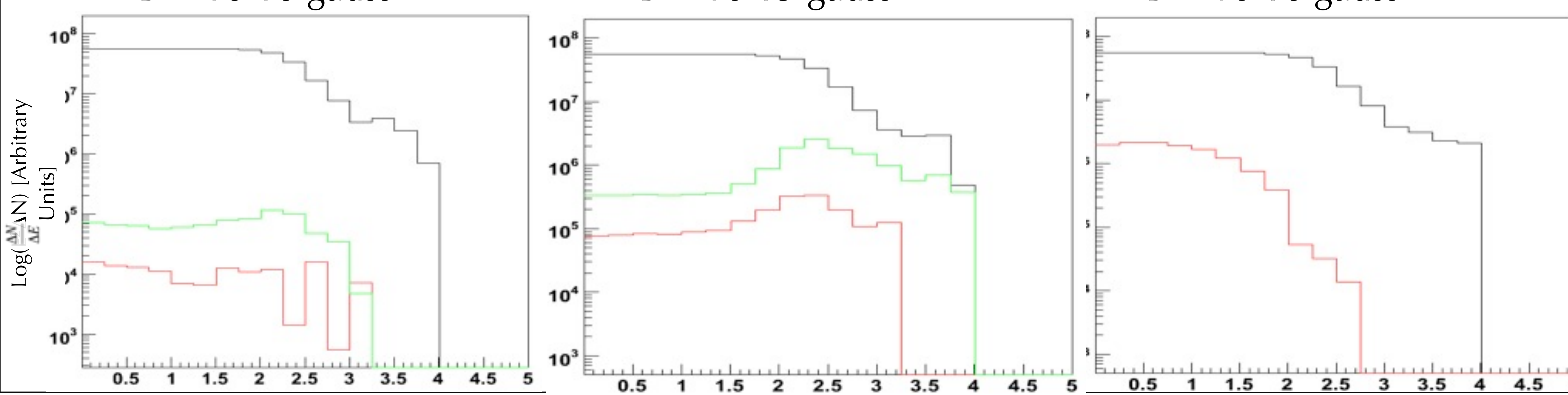
(from Tim Arlen, UCLA)

Z = 0.032, B=1x10^{-14} gauss
$dN/dE \propto E^{-\alpha}$, α=2.0, Γ = 10

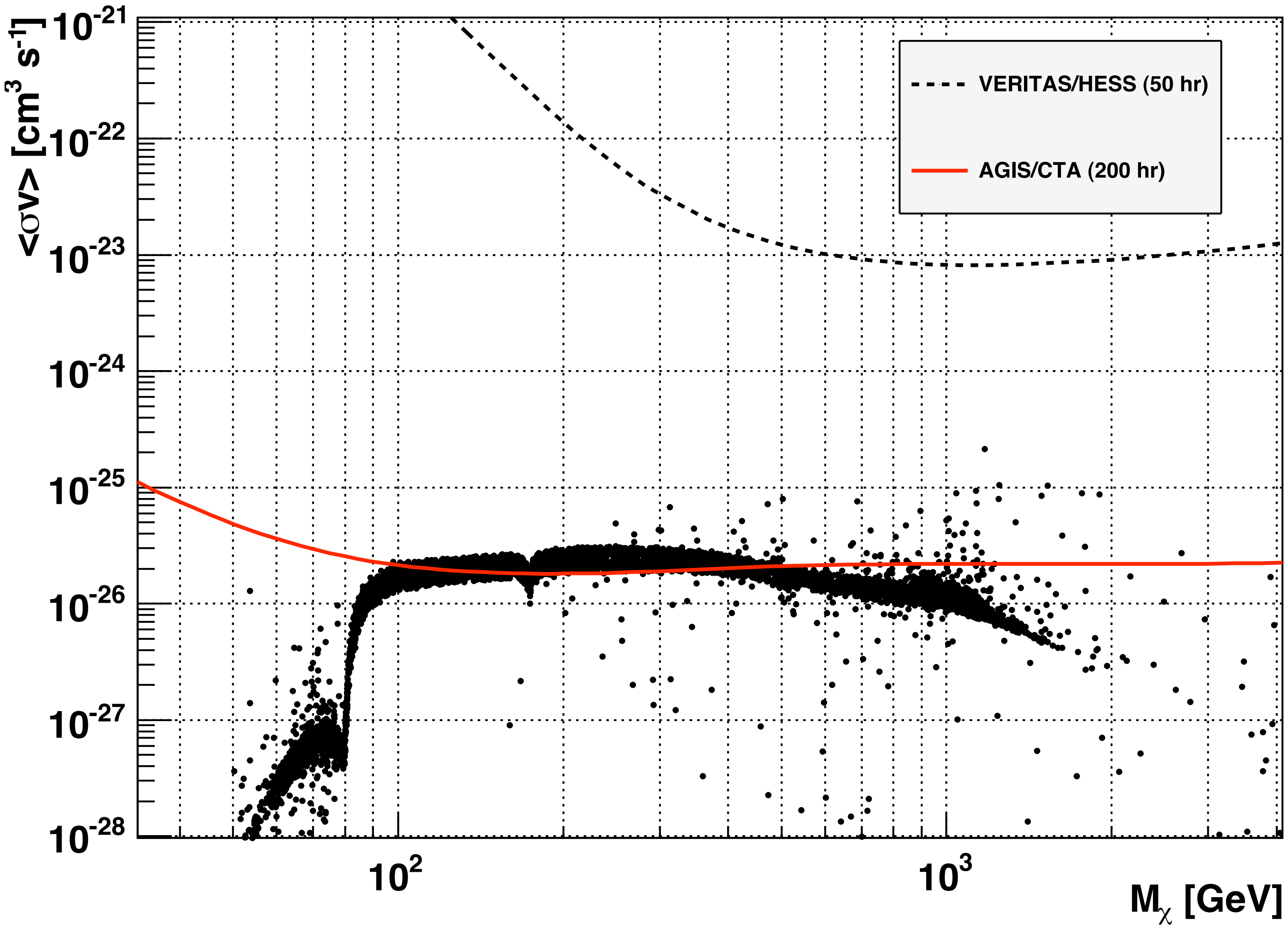


- Prompt
- Sec Pt Source
- Halo

B = 1e-10 gauss B = 1e-13 gauss B = 1e-16 gauss

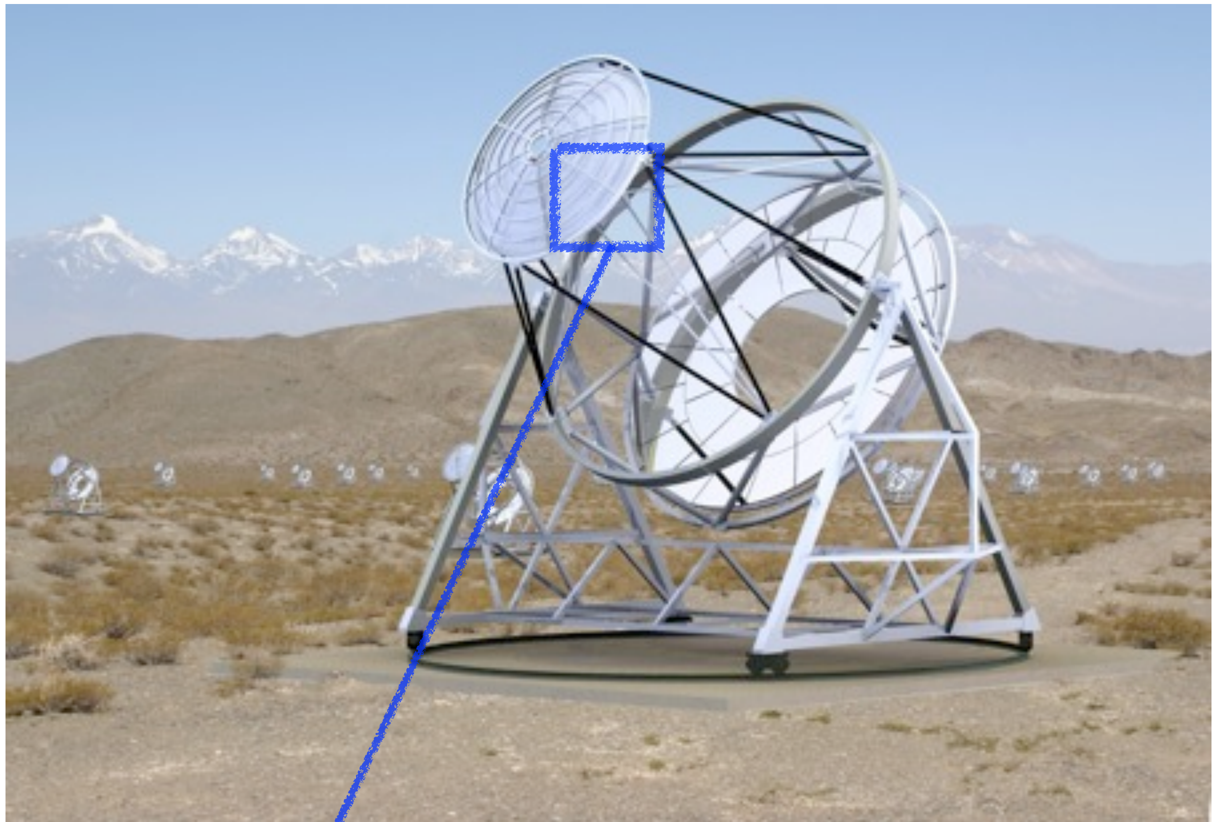


VERITAS/CTA DM Prospects

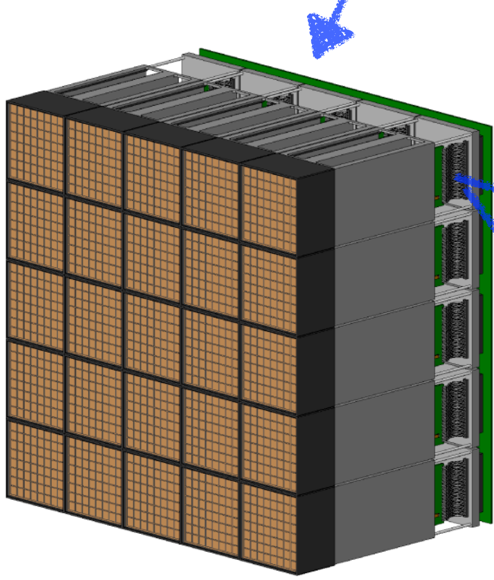


- With modest boost from halo substructure or Sommerfeld, future measurements of Dwarf galaxies or nearby substructure will probe the natural range of annihilation cross sections for much of SUSY parameter space.

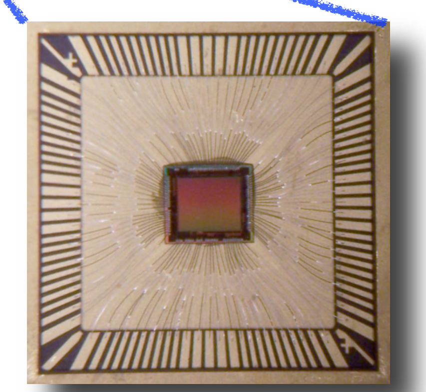
CTA-US Technology R&D



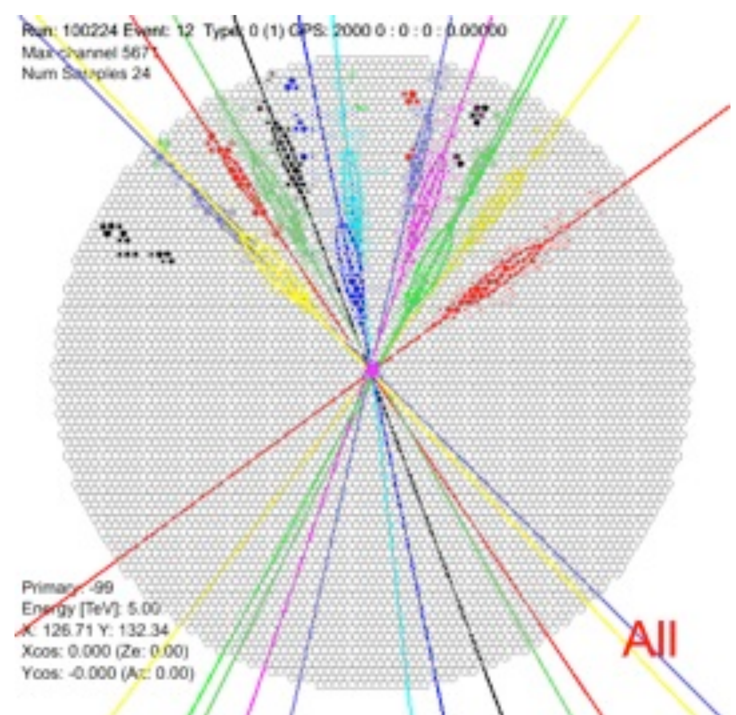
- Add 36 telescopes to existing 24-scope mid-sized telescope array.
- Collective effects in combining experiments - in large array, higher percentage of showers fall between scopes than beyond edge - lower energy threshold, better angular resolution, better sensitivity
- CTA-US group exploring Schwarzschild-Coulder for plate-scale reduction (MAPMTs), angular resolution, large corrected FOV (8 degree)
- Modular camera with SCA ASIC giving 16000 0.056 deg pixels with Gsps waveform sampling for ~$1M

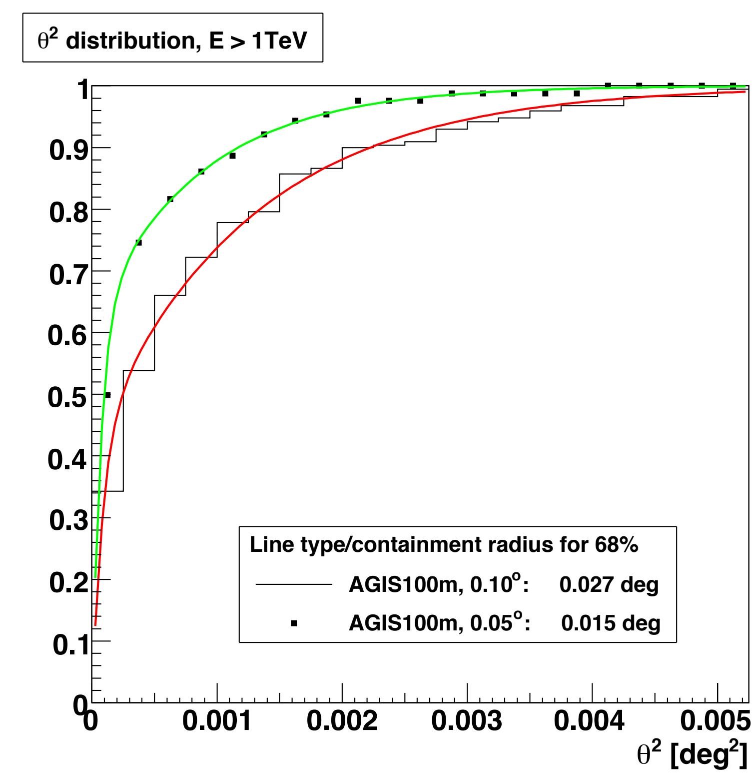


Modular MAPMT camera



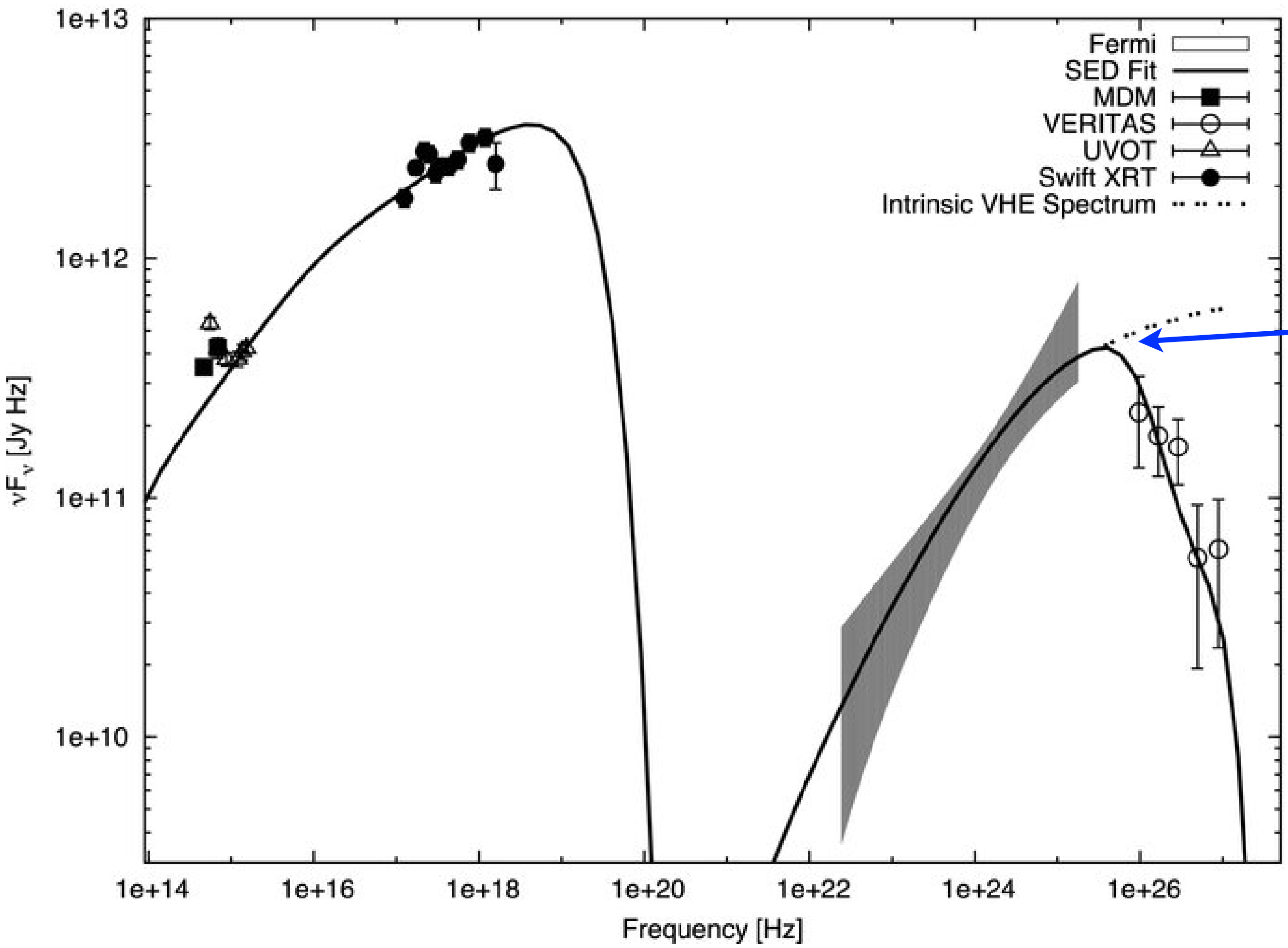
Switched-Capacitor-Array ASIC





Extragalactic Background Light

VERITAS/Fermi spectrum of RGB 0710+591



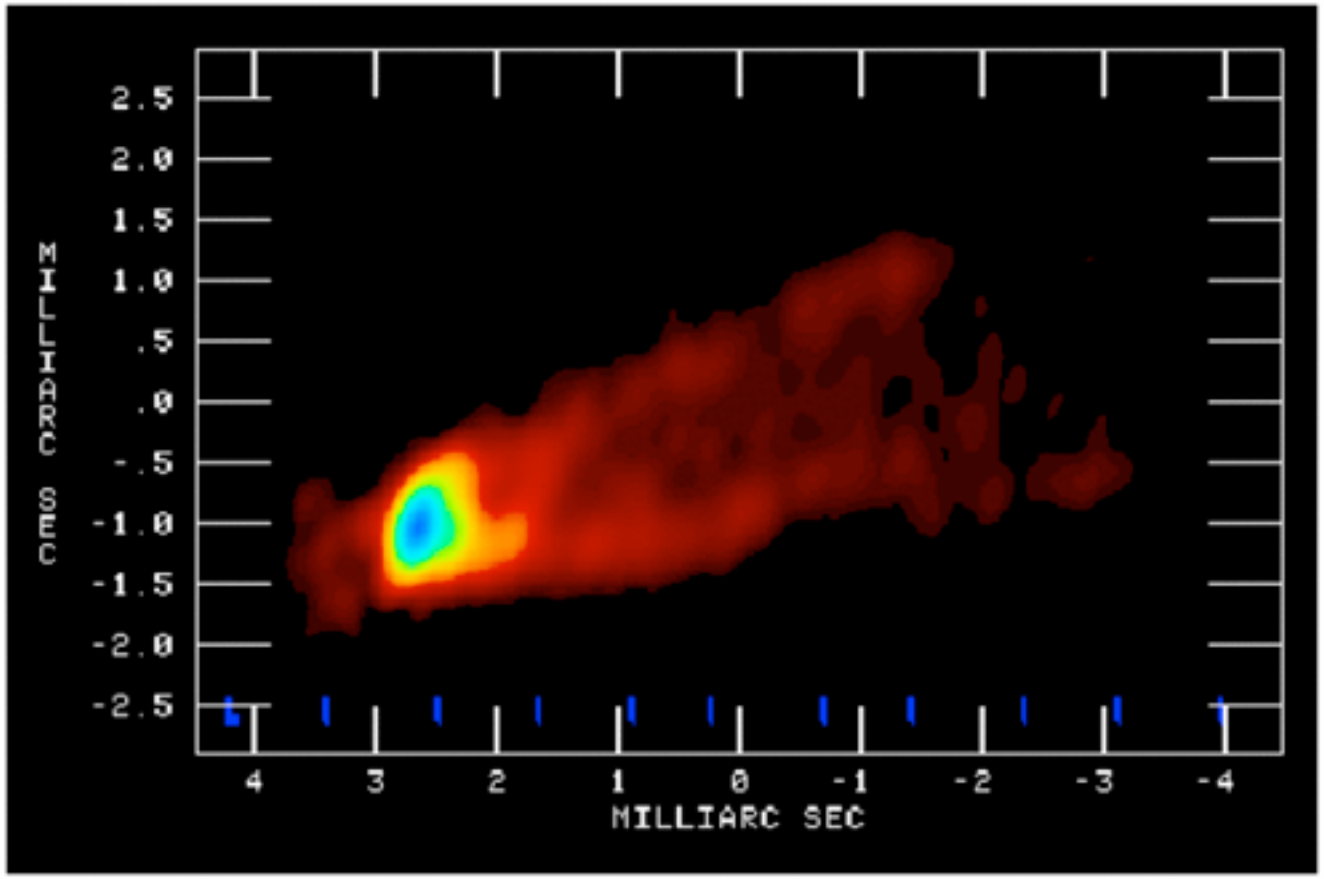
Spectral distortion from $\gamma_{\mathrm{TeV}} + \gamma_{IR} \rightarrow e^{+}e^{-}$

$\Gamma_{HE} = 1.46 \pm 0.17_{stat} \pm 0.05_{sys}$

$\Gamma_{VHE} = 2.69 \pm 0.26_{stat} \pm 0.20_{sys}$

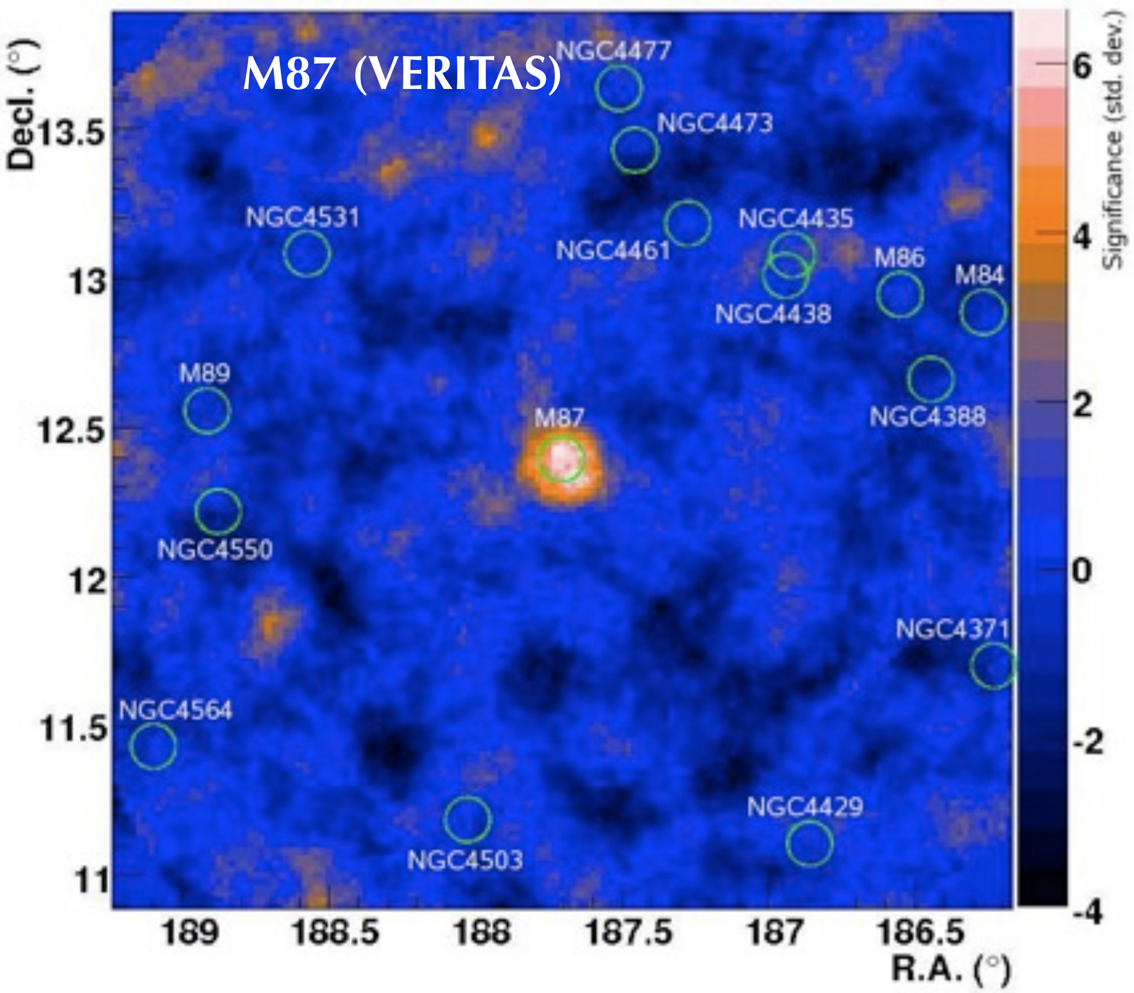
- VERITAS, HESS and MAGIC spectra, combined with Fermi spectra are beginning to result in *measurements* (not just upper limits) of EBL spectrum

M87: Radio Galaxy



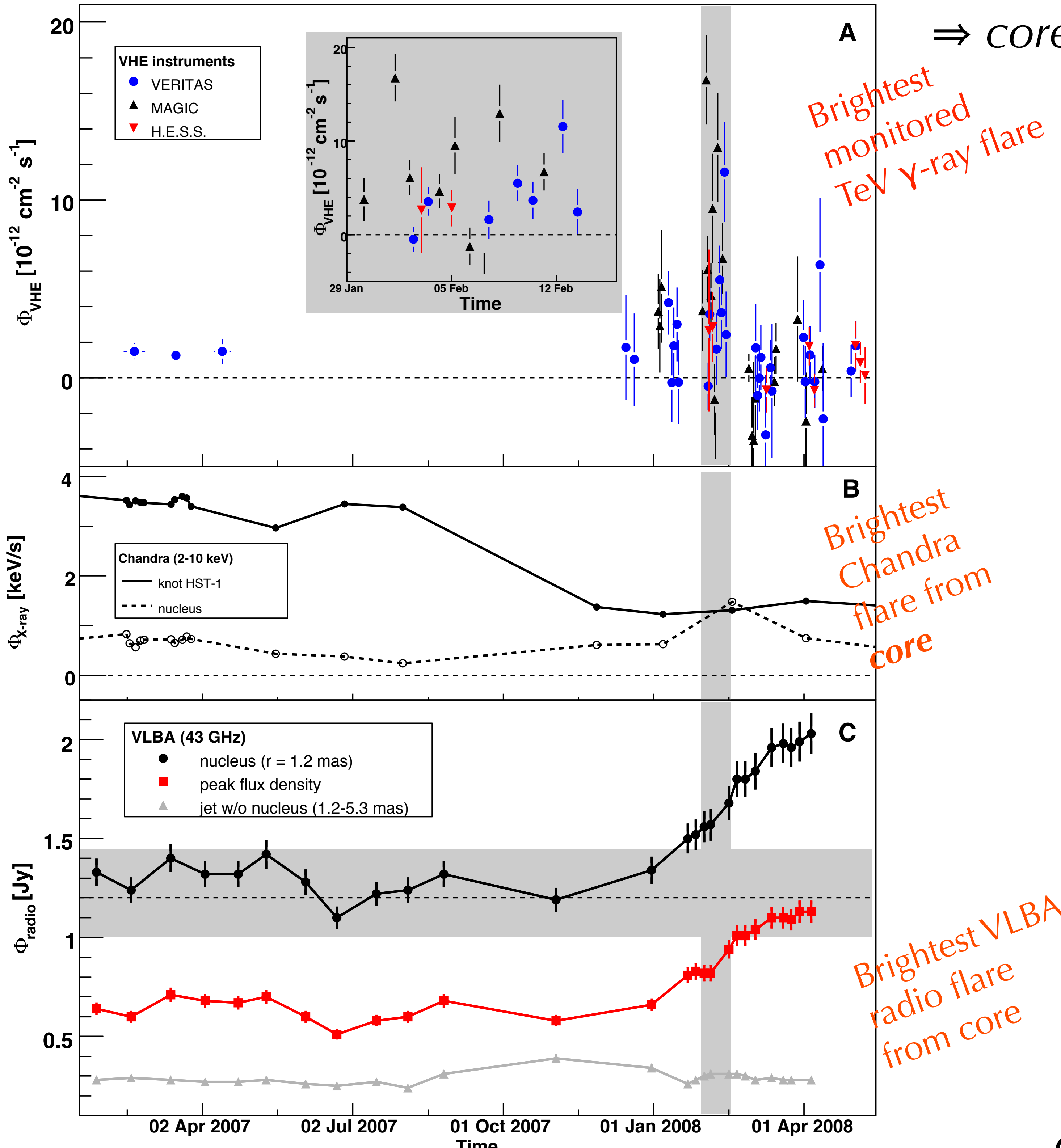
Walker, Lee, Junor & Hardee, 2007 43GHz VLBA data (1 Rs=0.37 mas, 1mas=0.078 pc)

- M87 one of the nearest active galaxies. VLBI reveals the innermost jet, but the central engine is still obscured due to synchrotron self-absorption, resolution limits



- VERITAS, HESS and MAGIC have detected flares from M87 - correlations with Radio reveal clues about the inner-most emission region

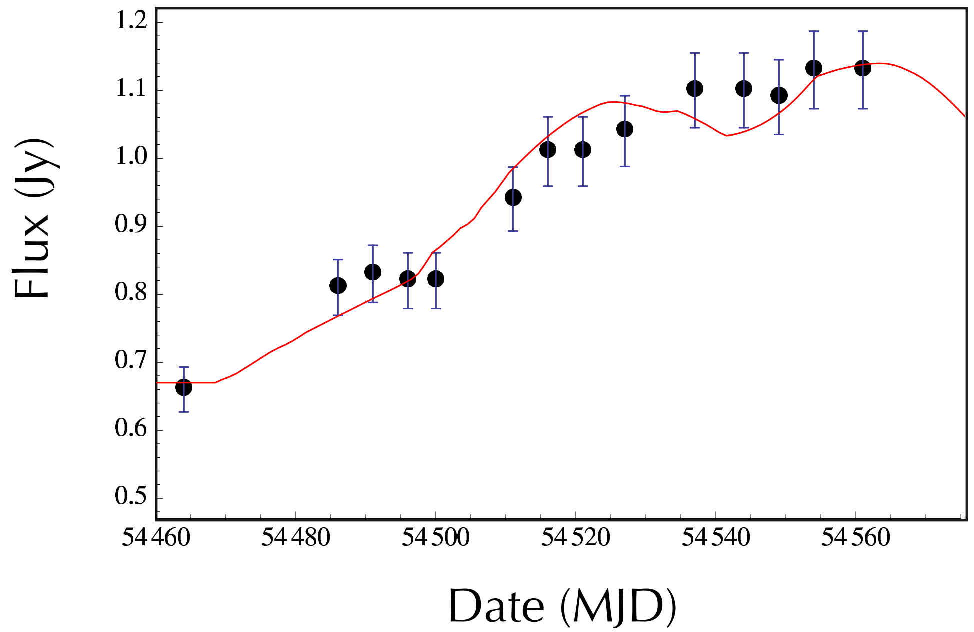
M87



(Acciari et al. 2009, Science, 325, 444)

⇒ *core R/X emission appears correlated with γs*

Model by H. Krawczynski (Acciari et al. 2009, Science, 325, 444)

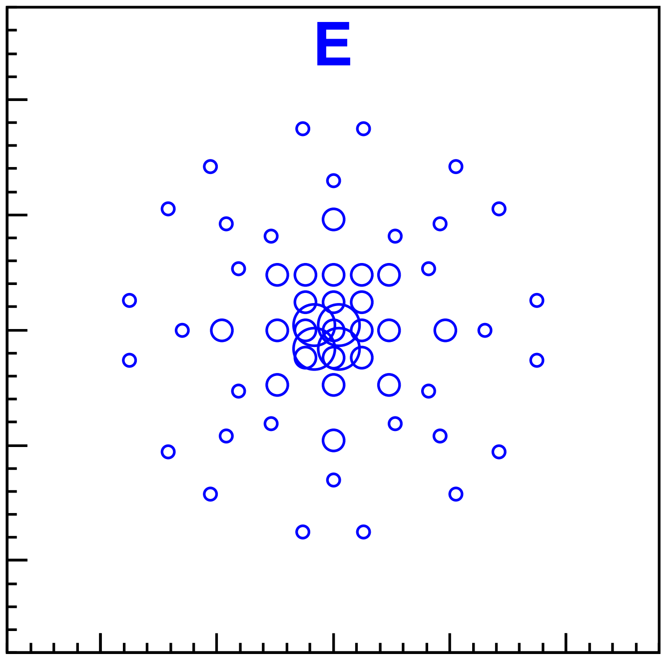


- Use γ-ray light curve as "source function" to inject electron population.
- Electron population cools adiabatically as plasma moves down "hollow cone".
- Account for differences in δ and in light travel time.
- Acceptable model fits for $\alpha=5^\circ$, $\theta=20^\circ$, $\Gamma = 1.01$, $\beta_{jet} = 0.14$, $B = 0.5G$.

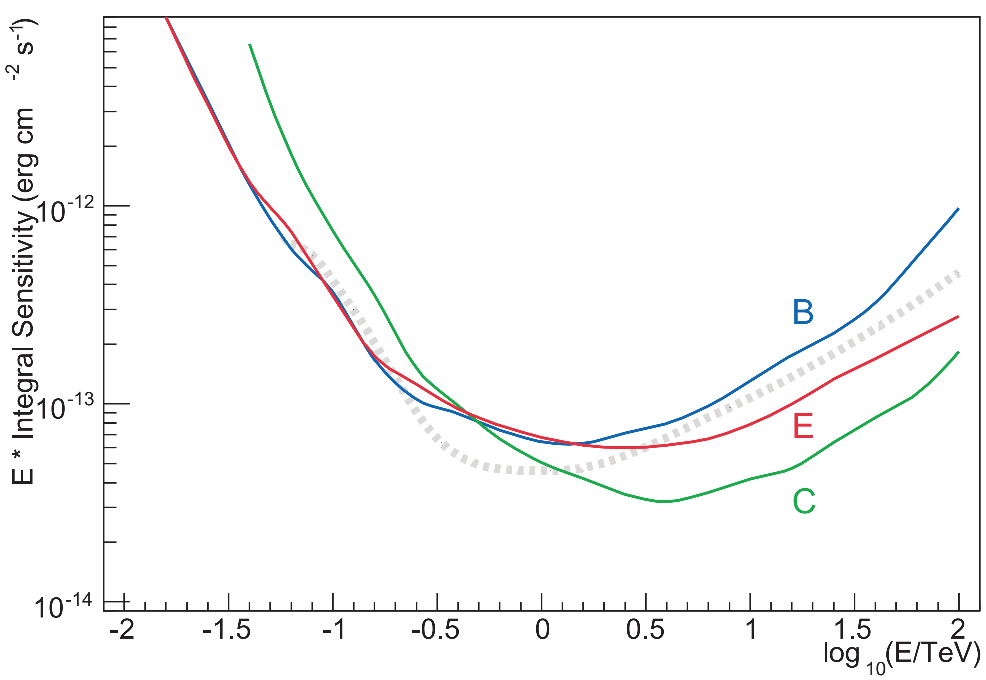
Gamma-ray emission region inside 50 R_G

CTA Performance

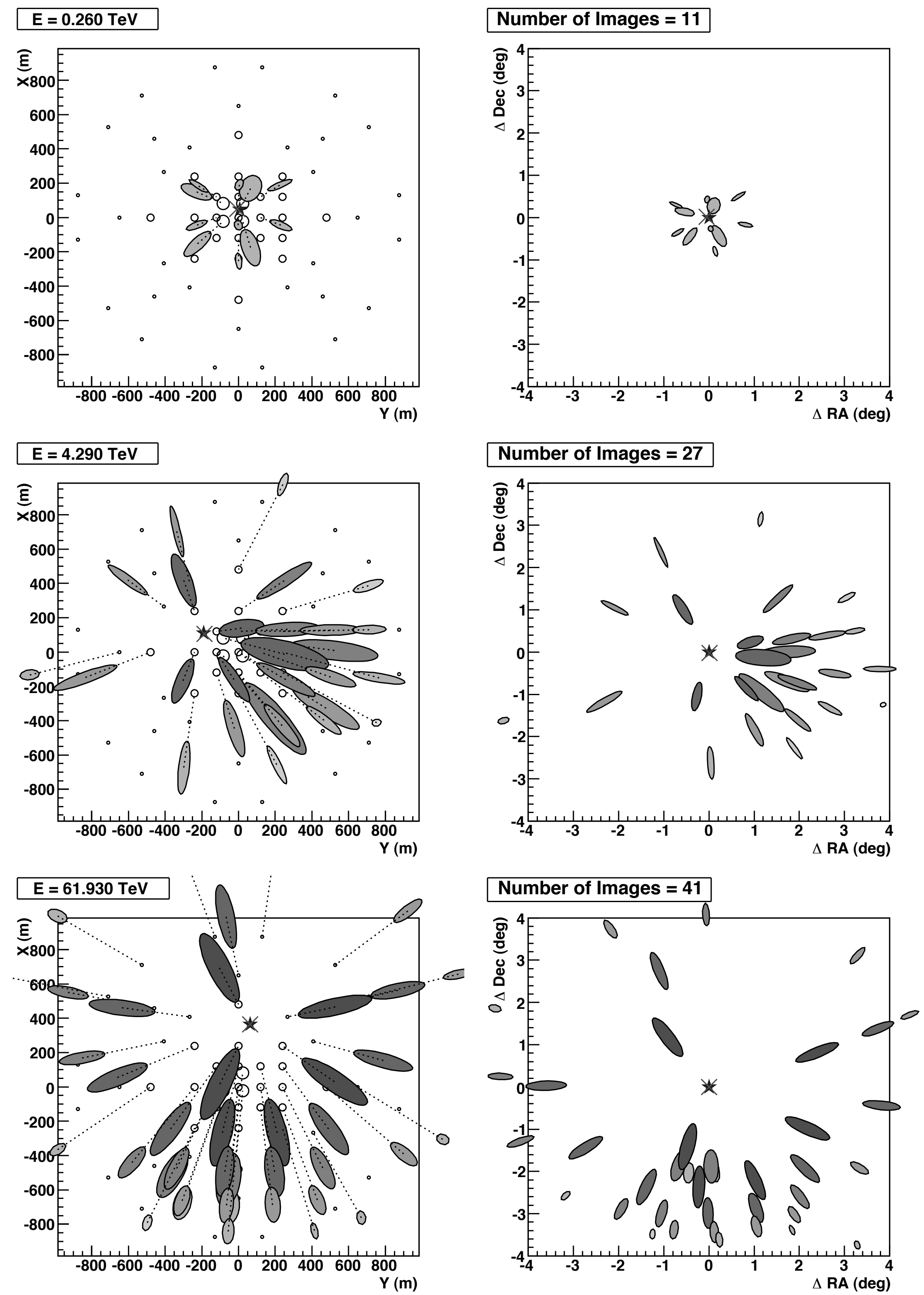
Possible CTA array configuration



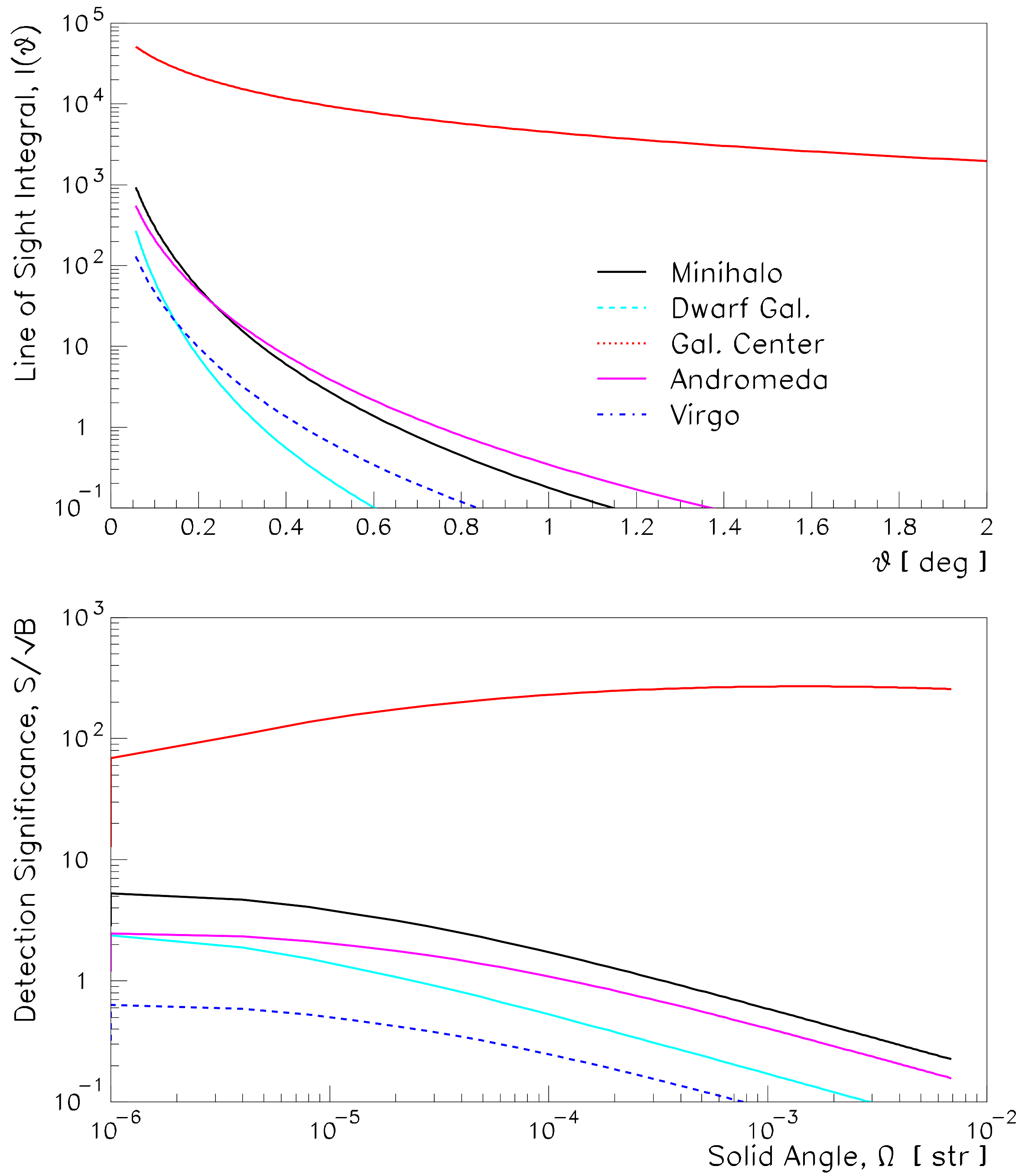
Differential Sensitivity for 50 hrs



Events for 260 GeV to 62 TeV gamma-rays



Gamma-Ray Halos



- Except for GC, most sources will appear point-like or not at all!